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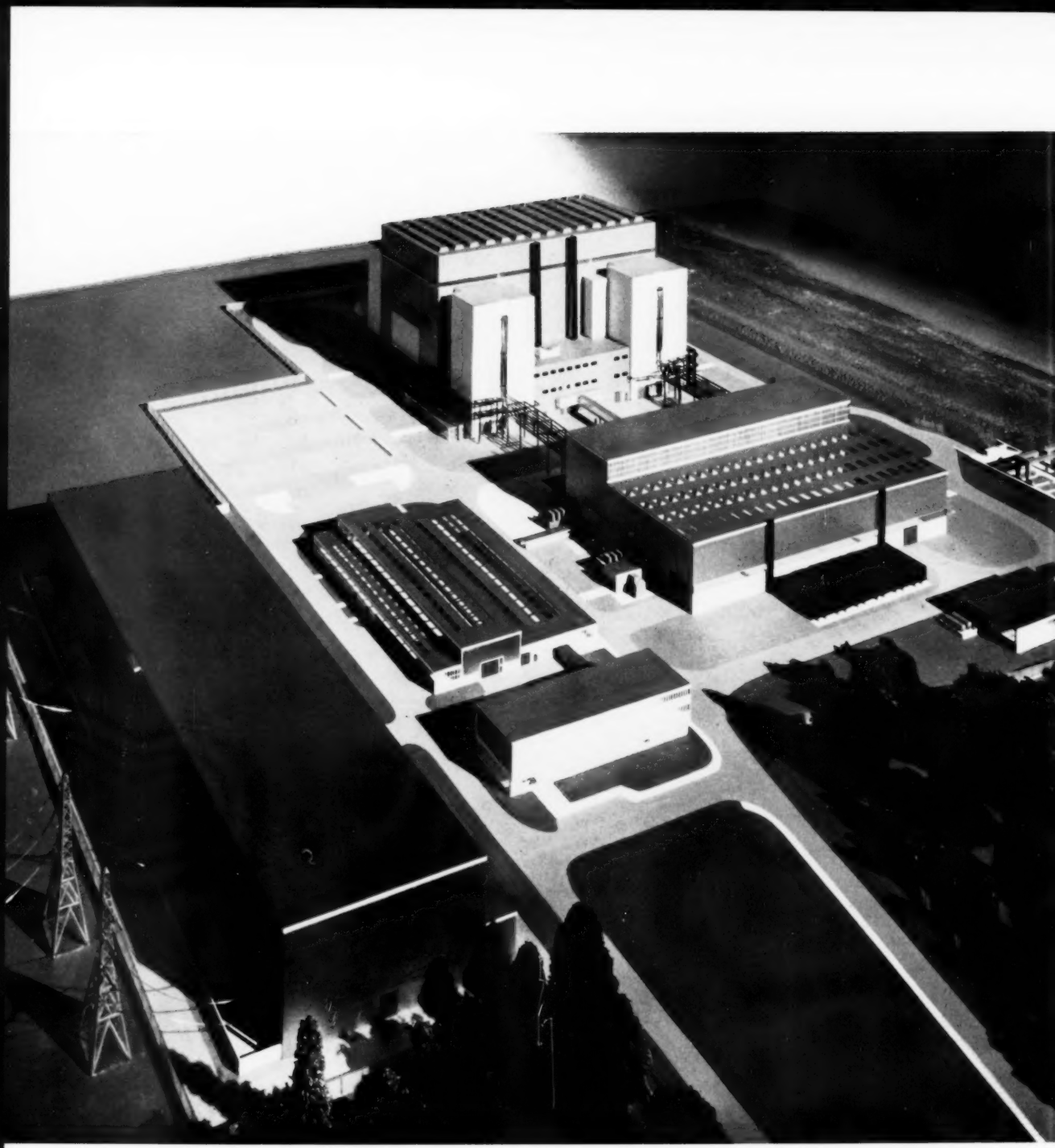

[photo.: The English Electric, Babcock & Wilcox and Taylor Woodrow Atomic Power Construction Com

SIZEWELL NUCLEAR POWER STATION. *Work will commence next month on a 580MW nuclear power station to be built at Sizewell in Suffolk by The English Electric, Babcock & Wilcox and Taylor Woodrow Atomic Power Construction Company. This model of the station shows :* (left) *indoor switchgear building :* (centre) *administration block :* (right) *turbine hall. Behind is the reactor building, a departure from previous British nuclear power station design in having both reactors housed at either end of one composite building.*

Editorial

IT is unusual to devote so large a proportion of this journal to one subject, but the present very wide interest in a.c. traction justifies, we believe, the exception made in the present issue. World-wide attention was attracted to the British Railways Electrification Conference held in London last year, and of the papers presented then, two are reproduced (Papers 16 and 25). Here, however, they are set in their context relative to the Company as Sections III and IV of an article describing 'English Electric' development work in a.c. traction—past, present and future.

As the largest manufacturer in Europe of diesel-electric and electric locomotives and equipment, it is fitting that the Company should be playing such a major part in the transformation of British Railways from steam to diesel-electric and electric traction. In the case of the latter, the successful running of the 'English Electric' 50c/s trains on the Lancaster-Morecambe-Heysham line, which for several years were the only 50c/s trains in Britain, no doubt influenced the decision to standardise on the 25kv 50c/s system for the modernisation of British Railways. The first a.c. multiple-unit train of this modernisation scheme, commissioned in November 1958, was fitted with 'English Electric' traction equipment, this being but the first of over a hundred that have since been put into service with conspicuous success. With the inauguration of the British Railways 50c/s main line from Manchester to Crewe last year, 'English Electric' 3000hp. locomotives also entered revenue-earning service.

At present, the Company is engaged in an impressive range of traction activities. Of the five types of diesel-electric locomotive 'English Electric' is supplying to British Railways, over one hundred of the much-praised Type 4 have been delivered and the first of twenty-two 3300hp. 'Deltic' locomotives are soon to be in regular service. Meanwhile, track trials of a 2700hp. gas-turbine-mechanical locomotive are providing information for future developments with this form of motive power. Overseas, orders for diesel-electric locomotives for East Africa, Ghana and the Sudan have been completed recently, and motor-coach and locomotive equipments are on order for Denmark and India, respectively.

AS work at Hinkley Point, Somerset—where the English Electric, Babcock & Wilcox, Taylor Woodrow atomic power group is building the world's first 500 MW nuclear power station—reaches the stage when that dominant feature of the site, the Goliath crane, is shortly to be dismantled, the need arises for the crane's transfer across the country for re-erection at Sizewell on the coast of Suffolk. Here, it will be used by the Group to build for the Central Electricity Generating Board a 580MW nuclear power station that will be the most compact, and yet have the highest output, of all the seven commercial atomic stations on order in the U.K. The major new design features which give compactness are the new type of reactor building containing both reactors, small diameter pressure vessels with thick walls, few boilers each of high capacity, and the use of only two turbines of large output, which reduces the size of the turbine hall.

'English Electric' Developments in 50 c/s Traction

I—INTRODUCTORY SURVEY

H. B. CALVERLEY, B.Sc.(Eng.), M.I.E.E., Assistant Chief Engineer (Development), Traction Department

A GREAT DEAL HAS BEEN PUBLISHED in recent years about the choice of the voltage and frequency to be used for railway electrifications. This article takes no part in this question ; it deals only with the single-phase 50 c/s system, and mainly with The English Electric Company's part in the very rapid developments in this system over the past decade. As early as 1950 'English Electric' was investigating what the future of this system was likely to be, and the year 1960 can be taken as representing the end of the initial development as far as application in Britain is concerned, this being the year in which regular operation of 50 c/s traction services commenced on the British Railways main line from Manchester to Crewe.

About ten years ago the S.N.C.F. (French National Railways) found that experiments they were conducting with locomotives designed to operate from a single-phase 50 c/s overhead wire at 20 kV or 25 kV showed great promise. As well as providing economy in first cost, owing to the lighter overhead wire equipment and the reduced cost of substations, this new system opened up the prospect of revolutionary changes in the traction equipments.

One of the most interesting features of the traction equipments was that several completely different types of equipment were possible, each having different advantages, and these could all be supplied from the same overhead wire. The S.N.C.F. soon placed large orders for four types of locomotive employing, respectively: on-load tap-changers and 50 c/s commutator motors ; on-load tap-changers, rectifiers and d.c. motors ; a.c.-to-d.c. motor-generator sets and d.c. motors ; and rotary frequency and phase convertors, and squirrel-cage induction motors.

Early developments by 'English Electric'

'English Electric' studies suggested that the equipments with rectifiers and d.c. motors would be favoured because the two types using rotating convertors tend to be heavy, and the 50 c/s commutator motor can be made to operate satisfactorily only by making it a complex and expensive machine. Although the a.c.-to-d.c. rotary convertor equipment has some points in its favour, as have the other types of equipment, the last ten years of development in Continental Europe has confirmed the correctness of 'English Electric' policy in concentrating development on the rectifier-type equipment.

The Company's first major development in this new field was the electrification of the Lancaster-Morecambe-Heysham line of British Railways, on which a regular service started in 1953. This development, which has been described in the March 1954 issue of this journal, and is the subject of Section II of this article, provided the Company with first-hand experience of the many problems associated with this new system.

Many experiments were tried on these Lancaster-Morecambe-Heysham equipments and much knowledge was gained, the value of which is evidenced in that the Company was the first manufacturer to produce multiple-unit equipments in bulk for the British Transport Commission. These equipments started regular service early in 1959, and are described in Section IV.

Equally important was the development of equipments for locomotives. For these, the rectifier type was again chosen. The development of suitable rectifiers and circuits was put in hand several years ago, and culminated in the locomotives described in Section III of this article.

L.V. versus h.v. control

One of the first important decisions made was to develop the 'low-voltage control' system for 'English Electric' locomotives for powers up to about 4,000 h.p. On this system the main transformer on the locomotive has a tapped secondary winding, and an on-load tap-changer operating on this winding feeds directly the main rectifiers, which in turn feed the traction motors.

While such a circuit might appear to be an obvious choice, the Company is in fact almost alone is using it. The explanation of this is interesting, and is best seen by looking back to pre-war conditions. A.C. traction was, by then, highly developed in Continental Europe but only on the 16⅔ c/s system, and this system used a.c. commutator type traction motors. These motors can be built for satisfactory commutation conditions only by using a large number of poles, which results in a motor of very high current rating at very low voltage. For a 3000 hp locomotive the traction motor rated current might be as high as 2000A, thus for four motors in parallel an 8000A tap-changer would be needed. Because of the difficulties of switching such heavy currents the 'high-voltage control' system was developed. This system uses an auto-transformer, connected at one end to the line and at the other end to earth, which is tapped at twenty to forty points distributed along its winding. A tap-changer operating on this winding feeds a fixed-ratio transformer, which in turn feeds the traction motors. Tap-changing is therefore carried out at much smaller currents, but at much higher voltages, than with a low-voltage system.

The conditions, however, are very different in the case of rectifier locomotives. On the 'English Electric' locomotives for British Railways, for example, the rated current per motor is about 700A, i.e. about one third of that of 16⅔ c/s locomotives. Tap-changing on currents of this magnitude is not at all difficult. Section III of this article explains how, by the use of special circuits, the arcing duty on the tap-changer contacts has been reduced to small proportions and also the number of contacts has been reduced. This refers respectively to the limitation, by means of resistance, of inter-tap circulating current and the 'twice-round' tap-changing scheme in conjunction with the three-wire bridge circuit with asymmetric tap-changing.

This l.v. control allows a minimum of equipment weight and a straight-forward transformer design. The electrical contacts are all readily accessible and are not under oil. One of the outstanding advantages, however, when compared with h.v. control, is that of economy in power demand.

As a basis for comparison it is reasonable to assume that, when on the tapping giving maximum output voltage, the designed percentage reactances of the transformer equipment for the h.v. and l.v. control systems will be equal, being governed by considerations of fault currents. Thus the locomotive performance, power factor and efficiency will be the same on this tapping for the two types of control. However, in the case, for example, of the tapping corresponding to a train speed of half that at the top tapping, the voltage regulation will be greater for h.v. control for two reasons : firstly, the percentage reactance will then be more than twice that for the l.v. scheme ; and secondly, the transformer resistance loss will be nearly three times that for the l.v. scheme. Consequently, in order to achieve this particular train speed it would be necessary for the h.v. scheme to use a tapping corresponding to a higher no-load voltage ; therefore the line current would be greater for a given motor current. In other words, for the same input power to the motors the h.v. control scheme has a lower efficiency and a lower power factor.

Although the gains quoted above are effected only on tappings below the top one, the all-the-year-round reduction in current consumption will be appreciable, particularly for mixed traffic locomotives when working to fairly low speed limits. The use of l.v. control will also help the overhead line protection problem in two ways : firstly by reducing the peak load currents in the

substation feeders, thus giving a bigger margin for minimum fault currents ; and secondly by improving the power factor, thus helping protection systems which discriminate by phase-angle measurement.

The foregoing explains how benefits to the power supply arrangements are obtained by using l.v. control and, of course, these advantages are greatly increased in the case of a railway system with dual overhead line voltages, such as the British Railways 25 kV/6·25 kV system. L.V. control allows the primary winding to comprise four sections which are connected in series for 25 kV and in parallel for 6·25 kV ; therefore the locomotive performance and current consumption are the same for both voltages. With h.v. control however, the 6·25 kV connection is made to a tapping approximately a quarter way from the earthed end of the tapped auto-transformer. Therefore, while running on the 6·25 kV line there is, even on the top tapping, a double transformation (6·25 kV/25 kV and 25 kV/l.v.), and the locomotive performance is bound to be inferior to that on the 25 kV line because of the much higher values of reactance and copper loss.

Rectifiers

The ' English Electric ' locomotives for the British Transport Commission are equipped with water-cooled ignitrons. The use of water, instead of air, for cooling the rectifiers has some advantages : it results in smaller rectifiers, increased thermal time-constant and greater flexibility in the arrangement of radiator air ducting. One problem however introduced by water cooling is the effect on anti-freeze agents of electrolytic currents flowing in the water pipes, due to the unavoidable differences in potential between the rectifiers. This problem was solved, after considerable research, by finding a suitable inhibitor and almost indestructible electrolytic targets.

The air-cooled excitron used on ' English Electric ' motor coaches can also be used on locomotives.

It is quite probable, however, that after the next year or two few locomotives will be built employing arc rectifiers ; even now many traction equipments are being built using germanium or silicon rectifiers.

Later developments

A multiple-unit train fitted with ' English Electric ' equipment incorporating silicon rectifiers was commissioned in June 1960 on the Colchester-Clacton line. The silicon rectifiers are mounted under the floor and it is believed that this is the first such installation. This train also has a novel scheme of control using a regulating transformer, made by Brentford Transformers Limited, which provides smooth control of motor voltage. This equipment is described in Section V.

Besides this, the Company is also building forty-two multiple-unit train equipments, and one locomotive, with silicon rectifiers. The locomotive is of particular interest and is described in Section VI of this article. The air-cooled silicon rectifiers are preferred to the mercury-arc rectifiers because of the elimination of pre-heating, and the smaller space occupied. They present such problems as protection against voltage surges, division of inverse voltage and current sharing, but these are being solved.

The opportunity is being taken of installing on this locomotive a novel scheme of tap-changing which was demonstrated on the test bed in mid-1960. This scheme uses transductors to effect smooth control of traction motor voltage and almost to eliminate arcing at the tap-changer contacts. The saving in space inside the locomotive body, due to the use of silicon rectifiers and the transductor scheme, allows a 1000 kW rheostatic braking resistor with its control equipment to be fitted.

The future

It will be observed that the principle of tap-changing on the l.v. side of the transformers has not only already been applied successfully in the production of the smallest and lightest 3000 hp. locomotive for British Railways, but is being developed further, now that silicon diodes are available, in the form of transductor control. It is expected that in the near future the transductors themselves will be replaced by ' silicon controlled rectifiers '.

It is thought that this last-mentioned scheme (Fig. 1) will constitute the maximum utilisation of materials and equipment at present foreseeable.

From this it follows that the weight and cost are minimised and the performance, efficiency and power factors are the highest obtainable. The advantages are summarised below :—

(i) Minimum weight of equipment, because a simple transformer with secondary tappings is all that is required. (There are no auxiliary transformers or reactors.)

(ii) Minimum cost. This follows from the fact that all the material and apparatus provided is efficiently utilised.

(iii) Maximum hauling capacity, because of the complete elimination of notching peaks and the favourable speed/tractive-effort characteristics.

(iv) Maximum possible power factor and efficiency, on all the running positions (e.g., fifteen) of the master controller.

(v) Minimum maintenance of tap-changer, because of the complete elimination of arcing at the power contacts.

Developments being thought about at present, but not necessarily yet economically practicable, include the use of static frequency and phase convertors which would allow multi-phase squirrel-cage induction motors to be used for propulsion.

There have been many developments in other traction equipment, such as control gear and auxiliary machines, but space does not permit their being dealt with here. It is hoped that this brief introduction will at least serve to show the rapid strides made recently, and still being made, even in the basic power circuits.

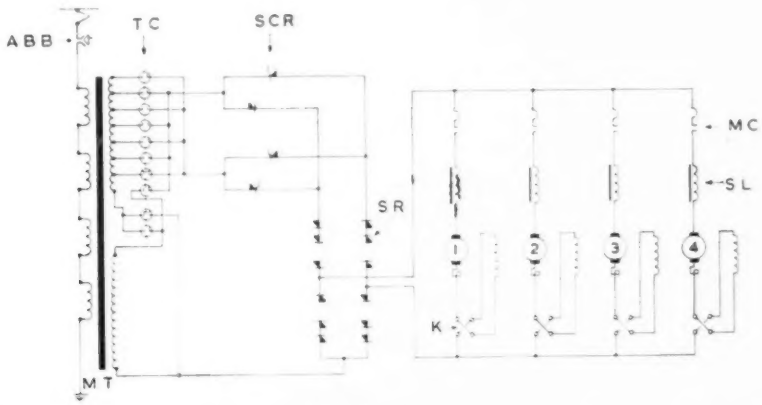

ABB	Air blast circuit breaker	MT	Main transformer	SL	Smoothing reactors
K	Motor reversers	SR	Silicon rectifiers	TC	Tap changer (non-rupturing)
MC	Motor contactors	SCR	Silicon controlled rectifiers	(1) (2) (3) (4)	Motors

Fig. 1—Simplified schematic diagram of power circuits for locomotive with controlled silicon rectifiers

II—THE FIRST 50 C/S RAILWAY IN BRITAIN

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D. G. OUSEY, B.Sc., A.M.I.E.E., A.M.I.Loco.E., Traction Outside Department

THE LANCASTER-MORECAMBE-HEYSHAM LINE has played an interesting part in the history of a.c. traction in the U.K. It was the first a.c. electrification in Britain, preceding that on the London, Brighton and South Coast Railway (' London Elevated Electric ') by about a year.

In 1908 the Midland Railway decided to electrify this section of track (nine route miles, twenty-three single-track miles), and thus pioneered the high-voltage a.c. low-frequency system, at 6600 V 25 c/s. This line was selected because it was hoped to attract traffic for Ireland via the newly-opened harbour at Heysham, it being intended to extend the electrification in due course via Skipton to Leeds. In 1923 the amalgamation of the Midland Railway with the London-North-Western Railway to form the London-Midland-Scottish Railway resulted in the diversion of most of the Irish traffic to Liverpool and Fleetwood, so that the importance of Heysham harbour dwindled.

The original rolling stock for this electrified line consisted of three trains, each with one motor-coach, the other coaches being un-motored. The electrical equipment for these three motor-coaches comprised two motor-coaches fitted with electro-magnetic control equipment manufactured by Siemens of Stafford (now The English Electric Company) and one motor-coach fitted with electro-pneumatic control equipment manufactured by the British Westinghouse Company of Trafford Park (later Metropolitan-Vickers Electrical Company). The motors in all cases were single-phase series commutator motors.

Initial experiments with 50 c/s traction

The above equipments had already reached their normal span of life by 1951, about the time experiments were started by the S.N.C.F. (French National Railways) at Annecy. In order to gain first-hand experience with this system of traction, The English Electric Company approached British Railways for permission to equip a trial motor-coach. This was granted, on the understanding that the Company equipped three train sets, sufficient to run a passenger service on the Lancaster-Morecambe-Heysham line. Such was the confidence in the equipment that this condition was accepted by the Company.

British Railways made available three old three-car d.c. trains which had become redundant on the L.M.S. North London lines (Earls Court—Willesden).

From the start of this conversion scheme the major consideration was to get a trial equipment into service as soon as possible, in order to obtain running experience with this new system of electric traction. By using standard components wherever possible, the Company succeeded in putting the first motor-coach into trial service in November 1952, just under one year after receiving permission

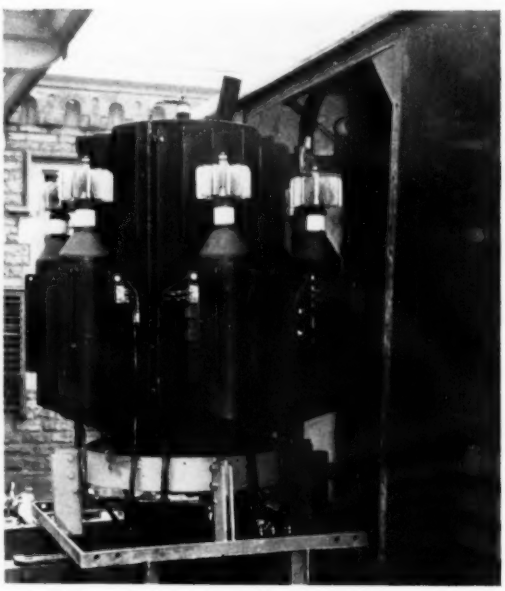

Fig. 1—A poly-anode rectifier being withdrawn from a coach

to proceed with the scheme. In referring to this achievement the willing co-operation of the Railway Carriage Works at Wolverton in making the necessary structural modifications to the coaches is here acknowledged.

The English Electric Company was thus first in the U.K. to put an a.c. train into service using rectifiers and d.c. motors.

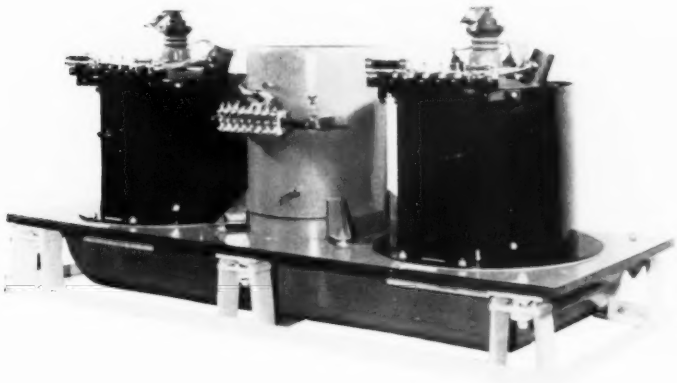

Fig. 2—A pair of excitrons with fan unit, designed for fitting in under-car case

It was decided to mount all the main equipment in a high-voltage compartment adjacent to the driver's cab, so as to have everything readily accessible for inspection, as this was to be a first experiment. (For future motor-coach equipments, the greater part of the gear would be mounted underfloor).

The old L.M.S. coaches had d.c. power equipment mounted in a small h.v. compartment behind the driver's cab and a luggage compartment behind that. To accommodate the larger amount of equipment required for the a.c. 50 c/s scheme these two compartments were combined into one h.v. chamber and a new luggage van was created at the expense of a part of the passenger space. The passenger saloons on the motor-coach and the two trailer coaches were fitted with new seating and a completely new heating and lighting installation.

The rectifiers used in the first place for all three motor-coaches were of the standard six-anode pumpless steel tank type already in use on stationary plant ; the only modification for traction purposes was the mounting of some of them on anti-vibration mountings. The main transformer was specially designed and was oil-forced-cooled with a separate air-blast radiator. The secondary winding was provided with tappings for l.v. control. The tap-changer was made from a standard motor-driven camshaft-operated power contactor group, as used on motor-coach equipments for the Polish State Railways. It was found that the cam-operated power contacts which previously handled the motor currents on this 3000 V d.c. equipment could with very slight modification handle the a.c. currents on this tap-changer. The d.c. current-carrying equipment, e.g. reversers and motor contactors, were of a type previously supplied to British Railways Southern Region contracts.

The traction motors were essentially normal d.c. motors but had to be capable of running on rectified single-phase a.c. Even with smoothing chokes added, the d.c. current still has a fairly high percentage a.c. ripple component, but tests proved that it was possible to use the type of motor being supplied for d.c. motor-coaches without modification.

The original pantograph was based on the general design as used on British Railways, Eastern Region (Liverpool Street-Shenfield Lines), but with a lighter design of collector pan and lighter spring pressures. Later, a new design of pantograph was made using aluminium alloy tubes and a skeleton collector pan, to reduce the inertia of the moving parts; this design is still working satisfactorily today.

Another interesting feature of this equipment is the special gas-actuated (Buchholz) relay. This is believed to be the first time that a relay of this type has been successfully applied to a transformer on a railway vehicle. Its moving parts and trip contacts were completely re-designed to make the relay suitable for traction conditions. In many years of service the relay has never operated incorrectly.

A detailed description of the motor coach equipments and of the fixed installations was given in the March 1954 issue of this journal. The equipment was installed on the motor-coaches at Wolverton, and put into service with very few teething troubles.

This type of equipment soon proved itself very reliable and all three coach sets are still running well and giving good service, one of the motor-coaches still using the original poly-anode mercury-arc rectifiers.

Trials with later designs of equipment

The poly-anode type rectifier, which was fitted on the first coaches, was used because it was already fully developed and available. It was recognised that it was bulky and that, for future motor-coach equipments, a more compact design of rectifier would be needed which could be mounted under-floor. An air-cooled single-anode mercury-arc rectifier of the excitron type suitable for mounting under-car was therefore developed. One of the three motor-coaches was taken out of service, the poly-anode rectifiers removed and the cases of single-anode rectifiers substituted. Although these cases were designed for under-car mounting, they were in fact installed in the h.v. chamber, partly because space on the underframe of these old type coaches was restricted, but also to allow easy access for examination during the trial running period. At the same time a new under-car type of main transformer was manufactured and this again was mounted in the h.v. chamber.

Regarding control gear, the original camshaft type tap-changer on this coach was superseded by an arrangement of individual electro-pneumatic contactors and relays. These were chosen to facilitate eventual mounting in cases on the underframe, but for the same reasons they were in this instance mounted in the h.v. chamber. The control circuit was novel in that, as far as is known, this was the first time that a scheme for automatic acceleration of an a.c. motor-coach using individual contactors had been evolved in which the progression from notch to notch was controlled by relays without the use of a rotating control camshaft. This modified coach was commissioned early in 1955 and is still running satisfactorily.

After about two years the excitrons were changed for a later type to gain running experience with the final type now used in large quantities on the London-Tilbury-Southend coaches, described in Section IV.

After these equipments had been running for some time, British Railways decided to modify one of the motor-coaches by fitting semi-conductor rectifiers of another manufacture. These three motor-coaches, all with equipment substantially of ' English Electric ' manufacture have therefore provided a useful proving ground for rectifiers of several manufacturers.

Comprehensive tests

This experimental electrification on the 50 c/s system was made use of by ' English Electric ' for the first attempt at carrying out system tests. By this is meant the organising of a comprehensive series of test runs during which (utilising radio communication) simultaneous sets of readings were taken in the substation and on the moving vehicles, using oscillographs, harmonic analysers and ciné photographs of panels of indicating instruments. As a result of these tests, it was possible to compare the actual characteristics of the complete installation under working conditions with calculated values based on various theoretical assumptions. The test results were used to illustrate the errors in the accepted theory and to justify a new approach. The whole subject formed the basis of an interesting paper presented to the Institution of Electrical Engineers in 1957.*

IT SHOULD BE NOTED that the Lancaster-Morecambe-Heysham line, although providing opportunities for trying out new designs of equipment, is an integral part of British Railways network and the trains equipped by ' English Electric ' are giving a regular and reliable service to fare paying passengers. Each train has run over 300,000 miles, and the passenger traffic receipts from this line have increased considerably since the service with the coaches described above was started, so that this first attempt at trying out a completely new system of electric traction has proved not only a success from the technical point of view but also a sound commercial proposition.

* *Paper 234OU, by Dr. T. E. Calverley and D. G. Taylor*

III—LOCOMOTIVES FOR BRITISH RAILWAYS

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S. C. LYON, Chief Design Engineer, Rolling Stock Design Department

THIS SECTION DESCRIBES the a.c. locomotives built for the British Railways modernisation programme. All fifteen locomotives ordered have identical equipment and mechanical parts, except that twelve are geared for 100 m.p.h. maximum service speed (type A) and three for 80 m.p.h. only (type B), but of course with increased rated tractive effort. The mechanical parts were built by The Vulcan Foundry Limited, a member of the English Electric Group of Companies. Unless otherwise stated, references are to type A.

Leading particulars

The leading particulars of these locomotives (Fig. 1), based on a line voltage of 22.5 kV, 100% secondary tappings, and half-worn wheels, are as follows :

Total weight	73·0 tons
Maximum axle load	18·3 tons
Weight of electrical equipment (including drive)	37·0 tons
Weight of two bogies (excluding motors and drive)	19·5 tons
Weight of underframe and body	16·5 tons
Length over buffers	52 ft 6 in
Bogie wheelbase	10 ft 0 in
Bogie centres	30 ft 0 in
Wheel diameter (new)	48 in
Gear ratio	25 : 76
Maximum service speed	100 m.p.h.
Maximum accelerating tractive effort (average)	40,000 lb.

Continuous rating at wheel :

	Full field	Weak field
Tractive effort	20,000 lb.	15,260 lb.
Speed	55 m.p.h.	72·6 m.p.h.
Power	2,940 hp.	2,950 hp.

The layout of equipment together with side and front elevations of the locomotive are shown in Fig. 2.

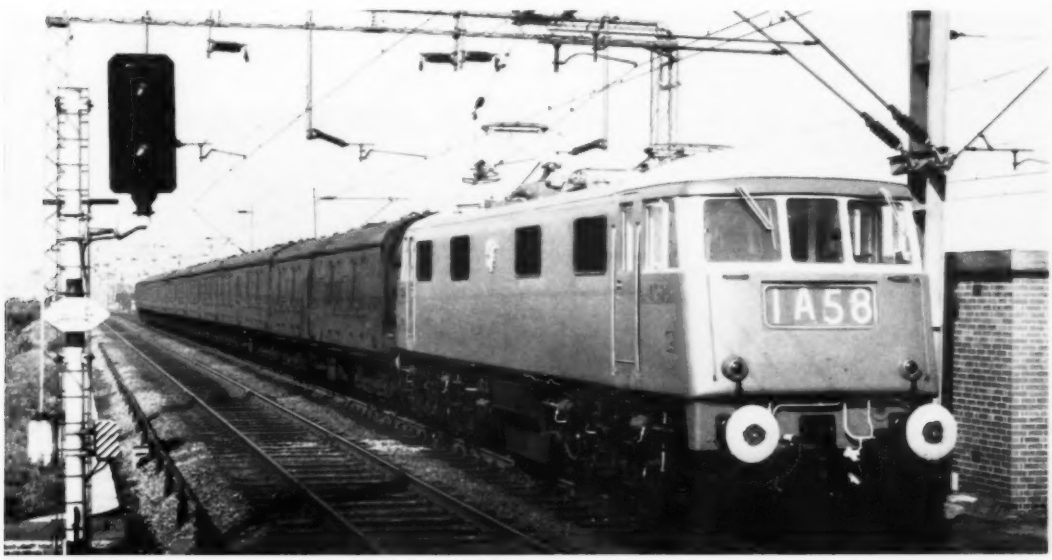


Fig. 1—One of the 25kV 50c/s locomotives now operating on the Manchester-Crewe section of British Railways

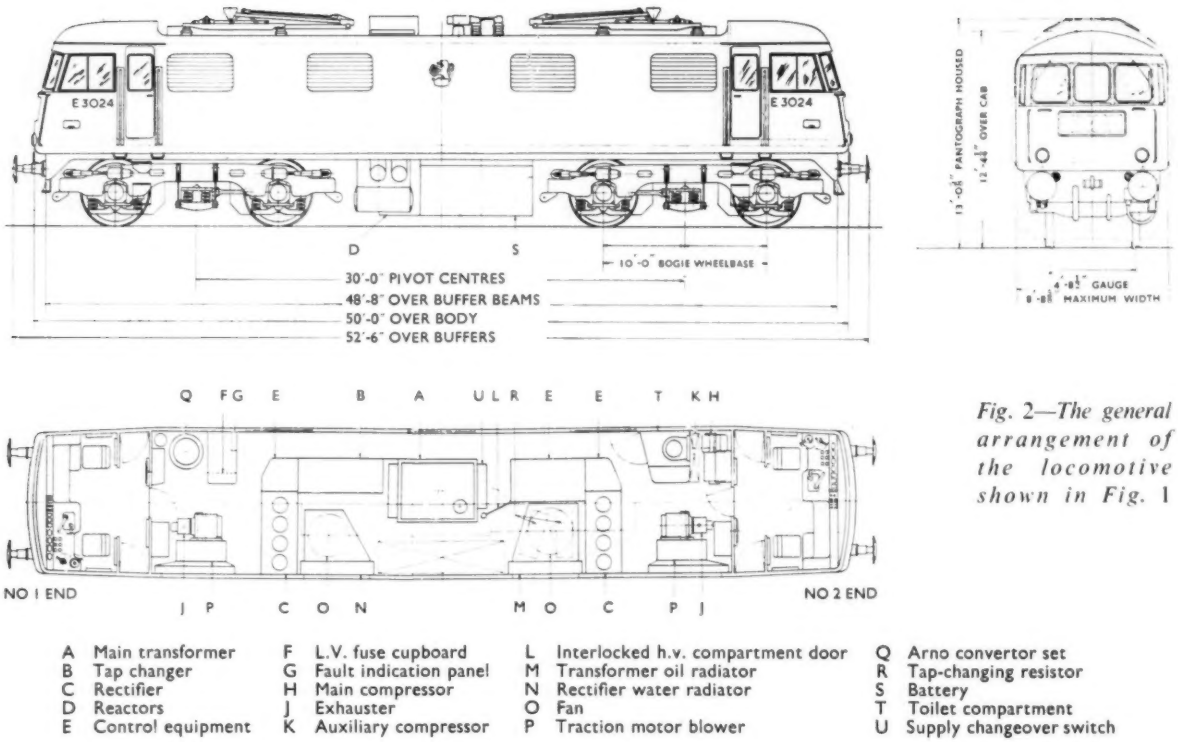


Fig. 2—The general arrangement of the locomotive shown in Fig. 1

A	Main transformer	F	L.V. fuse cupboard	L	Interlocked h.v. compartment door	Q	Arno convertor set
B	Tap changer	G	Fault indication panel	M	Transformer oil radiator	R	Tap-changing resistor
C	Rectifier	H	Main compressor	N	Rectifier water radiator	S	Battery
D	Reactors	J	Exhauster	O	Fan	T	Toilet compartment
E	Control equipment	K	Auxiliary compressor	P	Traction motor blower	U	Supply changeover switch

Fig. 3 shows the locomotive performance curves. Additional notches are provided to give approximately 5% increase in voltage if required, i.e. approximately 105%.

Description of circuits

Power circuits

The power circuits are shown in Fig. 4. Low-voltage control is attractive for the conditions obtaining on British Railways, because it allows full rated output on both 25 kV and 6·25 kV without increase in weight. Because of this, and also the known inherent advantages which l.v. control gives regarding power factor and efficiency, this system was adopted for the locomotives.

Current is collected by either of the two pantographs and feeds the primary winding of the transformer through an air-blast circuit-breaker and a supply changeover switch which connects four equal sections of the primary in series for 25 kV or in parallel for 6·25 kV.

A capacitive divider provides a suitable voltage for the operation of four detector relays associated with the control of the supply changeover switch.

The rectifiers are connected in two three-wire bridge groups and the two traction motors of a bogie are permanently connected in series across a bridge. The centre points of the motor circuits are connected to the centre point of the transformer secondary and also to earth. Hence the motors are effectively in parallel, making them less sensitive to wheel slip, and their voltage to earth is limited to a reasonable value.

Transfer from one transformer tapping to another is by closed circuit transition using resistance and reactance ; the reactance is left in circuit to give intermediate notches. Cam-operated contacts are used to select tappings and electro-pneumatic contactors are used for making or breaking the circuit.

At the continuous rating the current to be handled on the l.v. side of the transformer is

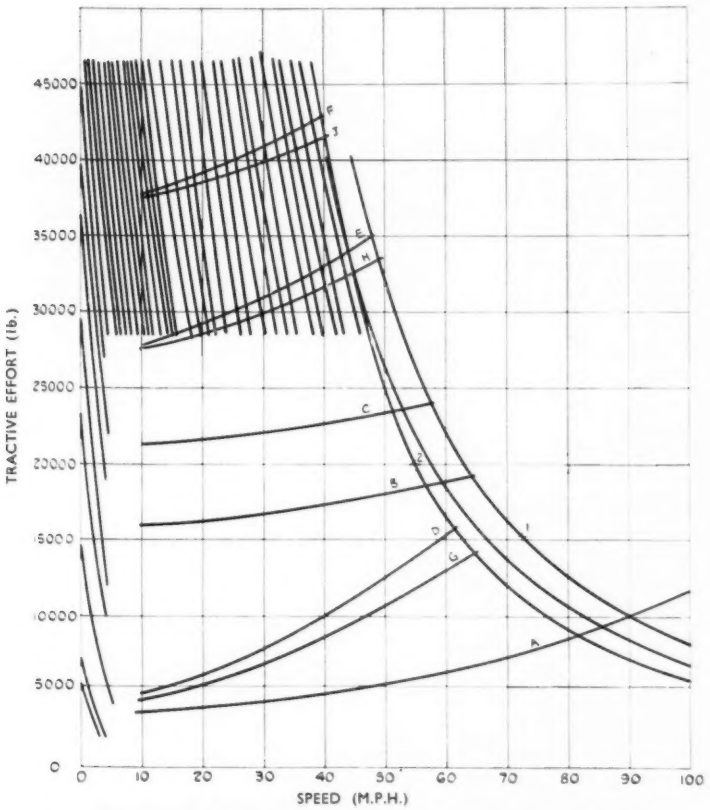
approximately 1,400 A. By inserting the resistor to limit circulating currents during transition, contact wear is reduced.

Asymmetric tap changing is used, each tap change affecting all four motors equally, but above half voltage the symmetrical conditions only are available as running notches in order to produce the best traction motor performance. Transformer tappings and selector contacts are used twice during acceleration, by using the tapped secondary windings first alone and then in series with equal un-tapped windings. The transition is effected by a winding grouping switch whose contacts do not make or break current and which also allows two reactors to be included in the commutating circuit up to half voltage. These reactors serve to steepen the locomotive speed current characteristics at the lower speeds and so reduce the notching peaks.

Two rectifiers operating bi-phase match satisfactorily the traction motor for voltage and current ratings, and are so used here. In order to rate the transformer at a kVA rating corresponding to bridge connection, the rectifiers supplying two of the motors are reversed in polarity. The result is the three-wire bridge circuit shown in Fig. 4.

There are thirty-eight economical notches with motors in full field. Two others are obtained by field tap, one at reduced voltage and the other at maximum voltage.

A smoothing reactor is arranged in series with each motor to reduce the current ripple to a value which is reasonable for motor operation. Four ammeters, one for each motor, are fitted in each driving cab, and indicate any mal-operation of the ignitrons, as well as indicating wheel slip.



TRAIN RESISTANCE CURVES FOR TRAILING LOADS ON GRADIENTS

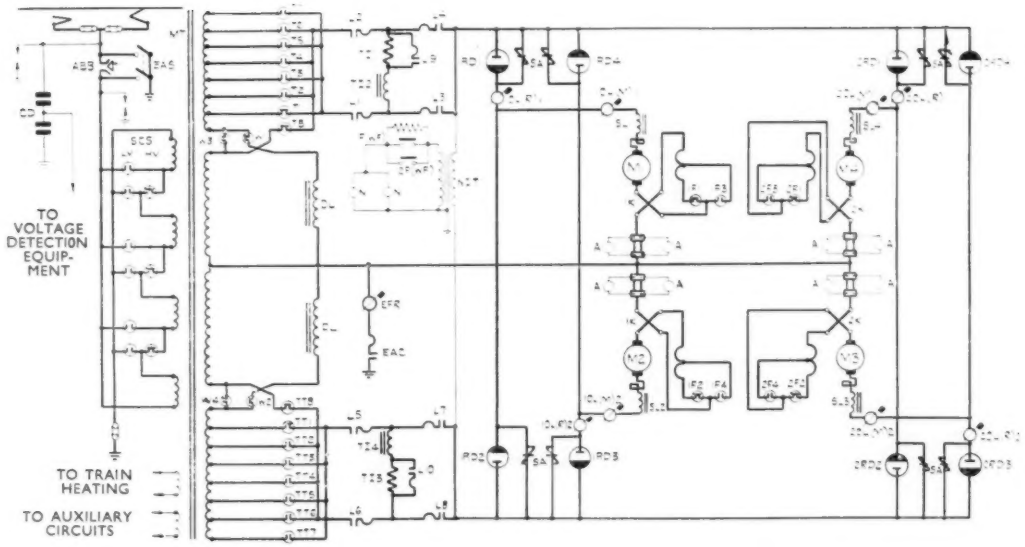
A	475 ton passenger on level	E	950 ton express freight on 1 in 100
B	475 ton passenger on 1 in 100	F	950 ton express freight on 1 in 70
C	475 ton passenger on 1 in 70	G	950 ton mineral on level
D	950 ton express freight on level	H	950 ton mineral on 1 in 100
		J	950 ton mineral on 1 in 70

Continuous ratings (1) Weak field (2) Full field

Fig. 3—Performance curves of a type 'A' locomotive, based on 22·5 kV line voltage and half-worn wheels

Auxiliary circuits

The auxiliary circuits are shown in Fig. 5. The main transformer has an additional winding for train heating and another for auxiliary supplies. The former provides current for train heating through two contactors. Protection is by fuses and an overload relay.



A	Ammeter	K	Reverser	RD	Main rectifier
ABB	Air-blast circuit breaker	L	Line contactor	SA	Surge arrestor
CD	Capacitive divider	M	Traction motor	SCS	Supply changeover switch
DL	Dropping reactor	MT	Main transformer	SL	Smoothing reactor
EAC	Earth contactor	N	Notch indicator	T, TT	Tap-changing selectors
EAS	Earthing switch	NIT	Notch indicator transformer	TI1, 3	Tap-changing resistor
EFR	Earth fault relay	OL (M)	Motor overload relay	TI2, 4	Tap-changing reactor
F	Field tap switch	OL (R)	Rectifier overload relay	W	Winding grouping switch

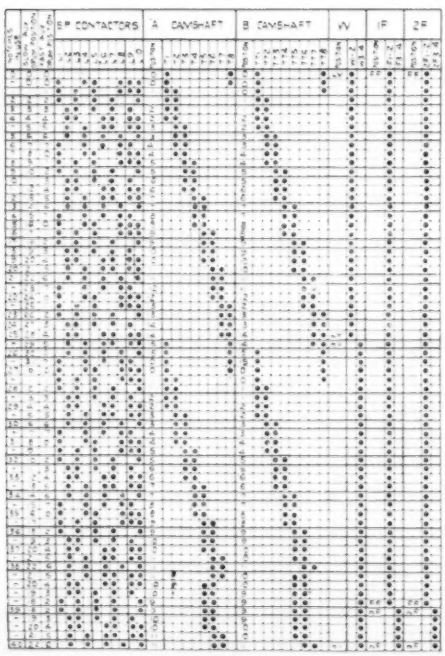


Fig. 4—Schematic diagram of the power circuits, and notching sequence chart

The Arno set consists of an Arno convertor direct-coupled to a d.c. generator and a small tachometer alternator. The battery is used to run the Arno set up to near synchronous speed, using the generator as a motor. At the appropriate speed the tachometer alternator causes the single-phase supply to be switched on to the Arno and opens the d.c. starting contactor. The Arno then drives the generator which is automatically connected to the battery and floats under automatic carbon pile voltage regulator control at 110V. The oil and water pump motors, being small machines, are permanently connected to the Arno three-phase supply and run up as soon as the single-phase supply is connected. The fan motors and blowers are connected to the Arno in sequence, with a time interval between each controlled

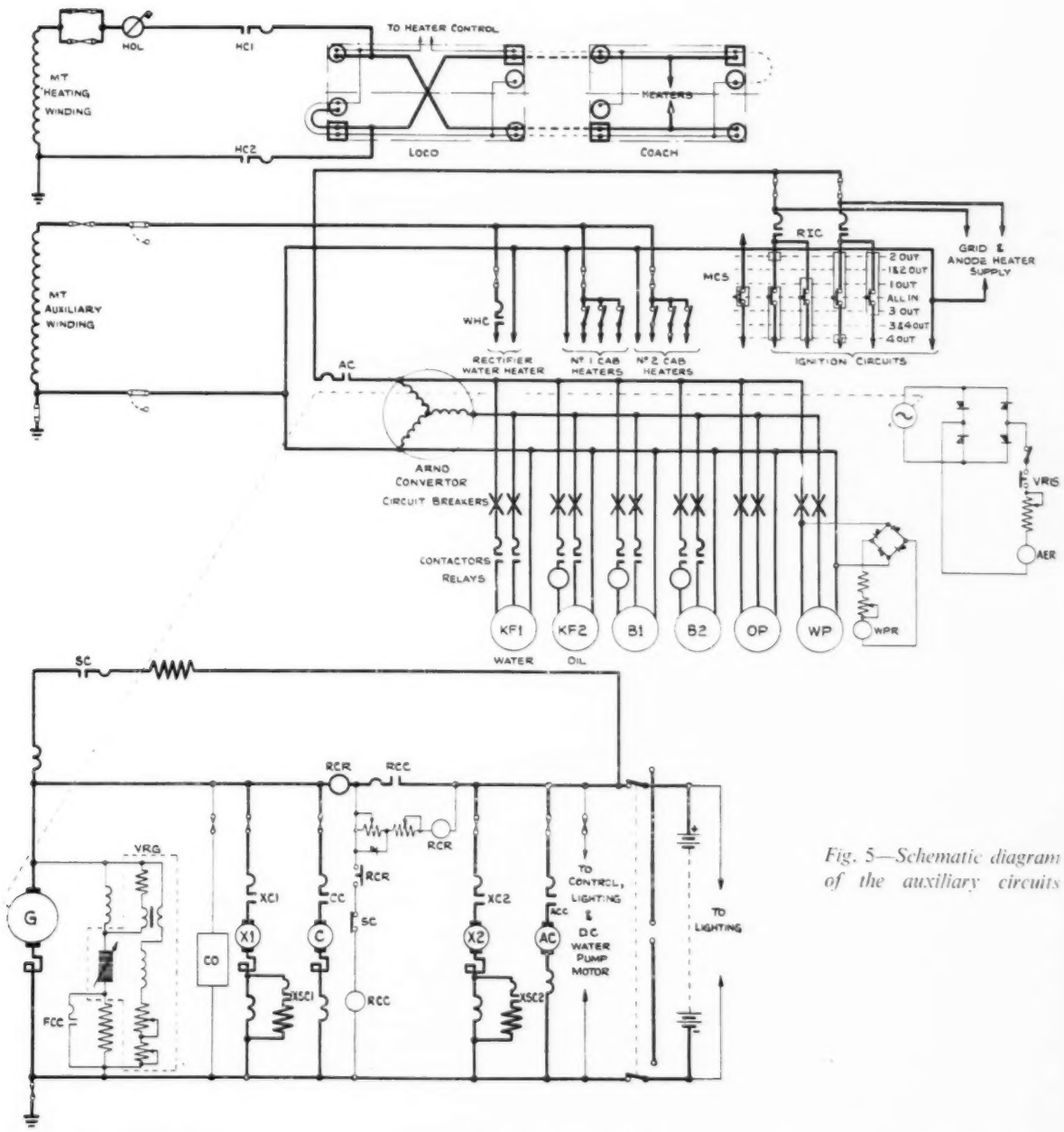


Fig. 5—Schematic diagram of the auxiliary circuits

AC	Arno supply contactor	HOL	Train heating overload relay	SC	Arno starting contactor
(AC)	Auxiliary compressor motor	HC	Train heating contactor	VR	Line voltage relay
ACC	Auxiliary compressor contactor	(KF)	Radiator fan motor	VRG	Voltage regulator
AER	Arno energising relay	MCS	Motor cut-out switch	WHC	Water heating contactor
(B)	Traction motor blower motor	MT	Main transformer	(WP)	Water pump motor
(C)	Main compressor motor	(OP)	Oil pump motor	WPR	Emergency water pump relay
CC	Main compressor contactor	RCC	Reverse current contactor	(X)	Exhauster motor
CO	Cooker	RCR	Reverse current relay	XC	Exhauster contactor
FCC	Generator field control contactor	RIC	Rectifier ignition contactor	XSC	Exhauster speed contactor
(G)	Generator				

automatically by a time delay relay. This scheme permits the use of simple machines without commutators or capacitors and gives constant speed to the a.c.-connected auxiliaries ; hence the cooling of apparatus is not dependent on line voltage.

The compressors and exhausters are d.c. machines. One exhauster is connected across the battery so that it can continue to run on loss of line voltage. The small auxiliary compressor is also connected to the battery.

By earthing one pole of the single-phase supply the a.c. auxiliary machines can be controlled by two-pole contactors and fully protected by two-pole circuit breakers.

Description of electrical apparatus

Roof-mounted h.v. equipment

There are two Stone-Faiveley pantographs, a Brown Boveri air-blast circuit-breaker and a Telegraph Condenser Company capacitive divider mounted on the roof. The transformer primary h.v. bushing protrudes through the roof ; the series/parallel changeover switch is mounted on one end of the transformer.

Main transformer

The main transformer, illustrated in Fig. 6, is of the shell type with forced oil cooling and a separate blown radiator. The core is built up of grain-oriented silicon iron and is clamped without through-bolts ; corner supports are provided to prevent movement of laminations in the horizontal plane.

The lower part of the tank forms a support for the core and windings ; the upper part carries epoxy-resin moulded secondary terminal blocks, the h.v. bushing, and various fittings.

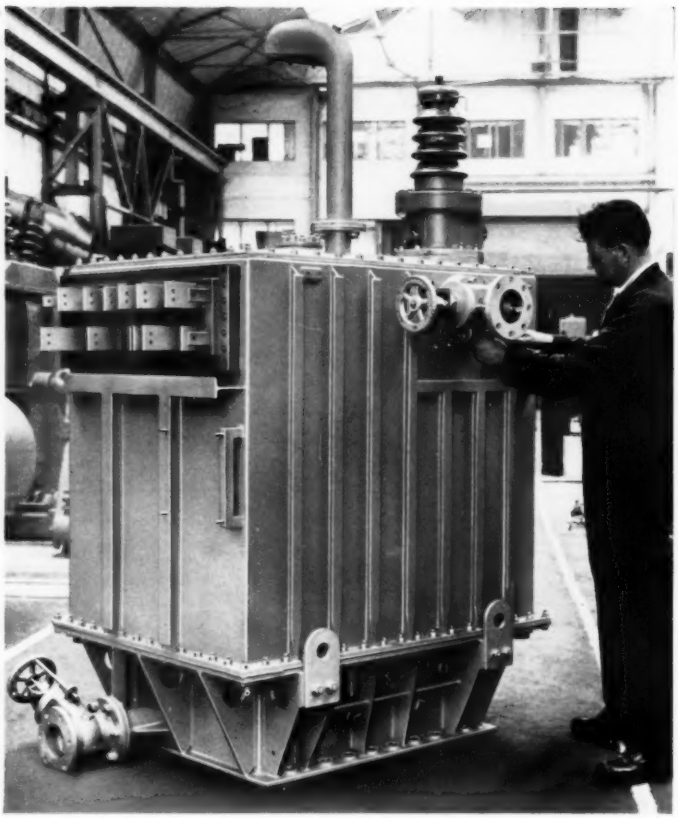


Fig. 6—The main transformer, showing high-voltage insulator for the primary terminal, the secondary tapping terminals and cooling oil connections

The transformer rating (to I.E.C.77) is :—

Winding	Primary	Secondary	Train heating	Auxiliary
Rated voltage	25/6·25kV	2,540V	906V	498V
Rated kVA	3,700	3,700	362	185

The transformer reactance is 10%.

Tap-changer

The tap-changer (Fig. 7) is a cam-operated controller in two halves on a frame with the engine and gears arranged between two cam-shafts. The

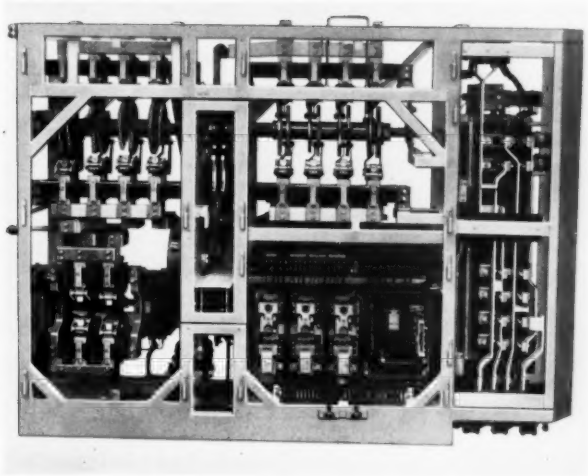


Fig. 7—Tap changer with covers removed. The right-hand end of the frame is entirely occupied with other control gear

main contacts are of the silver butt self-aligning bridge type. The main camshafts are operated through Geneva gears and movement is alternate so that only one camshaft moves at a time. The engine consists of three oscillating cylinders each carrying a piston and piston rod and arranged symmetrically around a crankshaft carrying the first driving gear. The engine is operated by control air through a reducing valve and is controlled for forward or reverse rotation by standard magnet valves. Position regulator contacts and electrical interlocks are operated by two additional camshafts which are driven through conventional gears from the engine. The whole mechanism is light and of low inertia so that stopping time is extremely small, stopping being effected by simply cutting off the air supply. Brakes are unnecessary.

Incorporated in the camshaft frame are the winding grouping switch for the transformer, the reverse and field tap switch and various control relays.

All current making and breaking is carried out by a total of ten electro-pneumatic contactors which are operated from the camshaft position regulator contacts. These contactors have laminated magnetic circuits for blow-out, silver butt current-carrying contacts and easily replaceable arcing tips.

Rectifiers

The locomotive contains two rectifier cubicles each containing four sealed ignitrons connected in a bridge circuit (Fig. 8). Each pair of ignitrons in effect feeds one traction motor.

The ignitrons are water cooled units 8 in. dia. and 32 in. high overall. Each tank contains two ignitors, one relieving anode and one energised grid, in addition to the anode and the cathode. The vacuum vessel is of stainless steel and 'Kovar-glass-Kovar' high temperature seals are used for the electrode insulation.

A water jacket with spiral guides surrounds the vacuum vessel and the cathode block is also water cooled. Heaters around the anode insulation prevent condensation of mercury in these areas. The cooling water is pumped through a fan-cooled radiator and thence to a distribution manifold which contains the water heaters. From this manifold, rubber pipes carry the water to the rectifiers and thence to the suction side of the pump. Special non-destructible targets are used at each end of each rubber tube. Thermostats in the suction manifold ensure that the water heaters are switched on and load application is prevented until the correct operating temperature is achieved, and thereafter, the water temperature is automatically controlled by a wax-bulb-operated valve in the radiator by-pass circuit. The water is treated with ethylene glycol and sodium tetraborate inhibitor.

Reactors

All reactors are situated in one tank and are oil cooled in series with the main transformer. The four d.c. smoothing reactors are each of about 3·1 mH at rated current and are specially arranged so as to practically eliminate stray fields and mutual inductive effects.

The two dropping reactors and two tapping reactors are each three-limb laminated cores with air gaps.

Driver's controls

These are standardised for all suppliers of equipments, to allow for a standard driving procedure.

Traction motors

The traction motors are four-pole d.c. machines, conventional in almost all respects. The frame is designed for mounting in the bogie frame and for use with the Brown Boveri resilient drive. There are two support arms on the axle side, one of which is purely to carry the motor, the other the Brown Boveri stub shaft and gear case.

The motors are continuously rated at 750 s.hp. 837 V 707 A mean when in full field and carrying undulating current with forced ventilation of 3,500 c.f.m. This rating corresponds to a line voltage of 22·5 kV. The permissible temperature rises of armature and fields are 150°C and 160°C respectively. The motors operate very satisfactorily with a ripple in the current of approximately 30% at the continuous rating.

The motors have fixed brushgear employing brushboxes with 'clock' type springs. Braids are fitted to the contact finger of the spring to carry current to the brushbox. Circumferential stagger of the brushes is used, there being three four-part brushes per brush arm, of which one four-part brush is staggered. One spring per pair of carbon pieces is fitted; pigtails are not fitted to the brushes.

The armature is lap-wound and is equalised at the commutator end for each slot. Twin conductors are used with glass braid covering cranked to enter the commutator risers. Class H insulation is used on the armature and field coils. The armature core and commutator are mounted on a common spider pressed on to the shaft.

The machine is not compensated and the interpoles are laminated. The interpole coil is edge-wound to assist heat dissipation and to reduce eddy losses in the conductors.

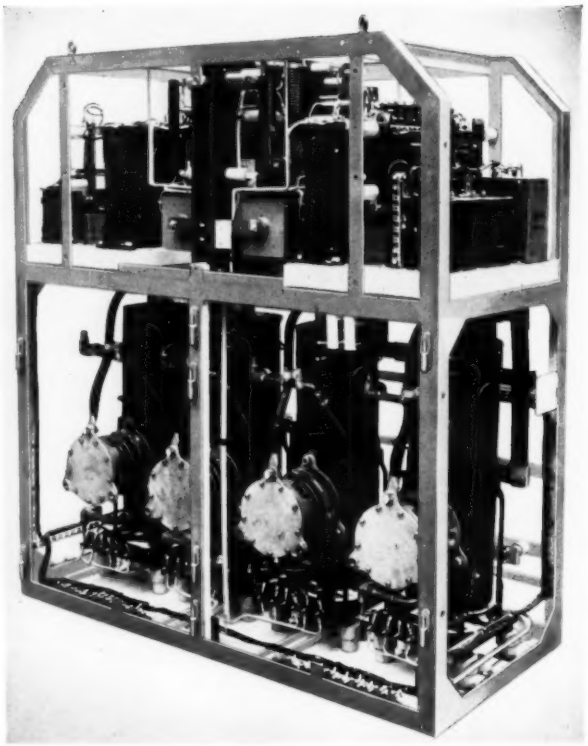


Fig. 8—One of the rectifier cubicles, containing four ignitrons. The surge arrestors can be seen in front, and the firing gear above

The main field coils are conventional three-tier coils with one tapping for the weak field notches.

Auxiliaries

The Arno convertor set comprises three machines : a single-phase three-phase Arno type convertor ; a d.c. generator ; and a small tachometer type alternator. It is mounted vertically in the locomotive to save floor space.

The Arno convertor is, in essence, a four-pole, three-phase, star-connected, squirrel cage induction motor. The stator windings are specially designed to enable it to run as a single-phase motor and to generate a three-phase electrical output simultaneously. The convertor can supply continuously a connected three-phase auxiliary

load of 60 hp., in addition to the mechanical load imposed upon it by the d.c. generator.

The d.c. generator is mounted above the Arno convertor, on the same shaft, and has a capacity of 20 kW. Its output is held constant at 110V by an automatic voltage regulator. A series starting winding is incorporated.

The tachometer alternator has a permanent magnet rotor and a two-pole stator winding, and provides a voltage proportional to speed.

The auxiliaries are as shown in the table below.

The makers of the pumps and main compressor are Worthington Simpson, and of the exhausters, Consolidated Brake and Engineering Company. A Nife 110V 85 A.H. nickel iron battery is installed.

Protection

Surge protection on 25 kV equipment is by two double rod-gaps, one on the condenser divider for line surges and one on the transformer h.v. bushing for switching surges. A surge arrestor of the silicon carbide type across each rectifier protects against the effects of ion-starvation in the rectifiers.

The secondary circuit earth is made through a contactor and a low impedance earth fault relay operating to open the air-blast breaker. The contactor is actuated directly by air from the pantograph cylinders and opens when the pantographs are dropped. An interlock on the contactor also opens the air-blast breaker. It thus prevents any circulating currents when the locomotive is being towed and there is an earth fault.

Faults in the transformer are detected by a Buchholz relay. A slow build-up of gas produces a warning and sudden production of gas is arranged to open the air blast breaker. An explosion vent, consisting of a pipe with a thin diaphragm covering the end, is arranged to direct any ejected oil on to the locomotive roof, from where it is drained to the track.

An over-temperature thermostat is fitted in the transformer oil and on operation opens the tapping contactors and returns the camshaft to its 'off' position, at the same time giving warning to the driver.

A motor flashover going to earth will trip the overloads and the earth fault relay, and open the air blast breaker.

Rectifier overload relays in the commutating path protect against back-fires and open the air-blast breaker.

The traction motor blowers and the oil-cooling fan motors are provided with no-current relays

No. per loco-motive	Function	Output	Supply	Rating	Speed (r.p.m.)
1	Arno convertor	See above	415V a.c.	—	1,490
	D.C. generator	110V d.c.	—	20 kW	—
1	Auxiliary compressor	3 c.f.m.(f.a.d.)	110V d.c.	1·5 hp.	1,500
1	Main compressor	22 c.f.m.(f.a.d.)	110V d.c.	6·1 hp.	1,450
1	Water pump (emergency)	—	110V d.c.	0·25 hp.	725
2	Exhausters	57·5/115 c.f.m. displaced	110V d.c.	2·5/5·25 hp.	715/1,430
1	Oil cooler fan	12,000 c.f.m.	415V a.c.	8·5 hp.	1,475
1	Water cooler fan	12,000 c.f.m.	415V a.c.	6·0 hp.	1,475
1	Water pump	64 g.p.m.	415V a.c.	1·5 hp.	2,850
1	Oil pump	350 g.p.m.	415V a.c.	6·0 hp.	1,420
2	Motor blowers	7,100 c.f.m.	415V a.c.	19·6 hp.	2,920

which give warning to the driver if they should stop. The warning is maintained even if the driver switches off the machines immediately after the occurrence of a fault. The water cooling system is fully protected by thermostats.

The control system for the auxiliary machines permits the blowers and fan to be shut down at stations to reduce noise, but a thermostat in the water cooling system can over-rule this control and re-connect these machines if the water temperature reaches a pre-determined value.

It is desirable in the event of loss of supply to maintain water circulation to the ignitrons ; therefore a small d.c. motor is provided for the water pump and is automatically connected to the battery, if for any reason the supply to the main pump motor fails.

Mechanical parts

Special study of the mechanical design was undertaken to meet the requirements of the specification. By comparison with existing electric locomotives in the same weight bracket it was considered that orthodox construction did not meet the required strength-weight ratio. The restriction imposed by low overall height in compliance with the British Railways loading gauge, the necessity to provide adequate clearance to earth from the high voltage equipment, and to accommodate relatively large diameter road wheels and high deflection spring gear, yet provide adequate gangways through the locomotive, indicated that a new concept in design of the superstructure was essential.

As a result the frame is designed as an integral stress bearing structure, the base being of shallow cellular construction and all body framing members of tubular section. This form of construction meets the essential requirements, i.e.,

(i) Resist static and dynamic vertical and longitudinal loads.

(ii) Accommodate a 200 ton compressive end load within the elastic limit of all materials.

(iii) Provide gangways through the locomotive not less than 5 ft 10 in high.

To achieve the result, resort has been made to special steels, aluminium alloys and glass-fibre construction. Steel castings have been avoided as much as possible and fabrication by welding is largely employed throughout.

The superstructure and bogie frames have been completely stress analysed and will be subjected to strain gauge tests in accordance with the loading conditions imposed.

Bogies

The bogies (Fig. 9) are designed for low maintenance ; practically all the operating gear such as primary and secondary springs, axleboxes, traction links, hydraulic dampers, brake cylinders and slack adjusters are externally arranged for ease of inspection. Brake blocks and cotters are directly accessible.

To minimise weight transfer during traction the bogie pivot and traction links are located at axle level.

Special care has been given in the design to promote good riding of the locomotive by provision of long range spring gear, swing motion bolsters, and close guiding of wheel and axle sets. The superstructure is metallically insulated from the bogies by means of rubber at the centre pivots, side-bearers and traction links.

To obviate any tendency to 'hunting' of the bogies on the track at high speed a proportion of the vertical load from the superstructure is transmitted through the side-bearers which incorporate coil springs with a pre-determined setting. Periodic movements of the swing motion bolsters are restrained by the fitting of transverse hydraulic dampers.

In place of the usual spring planks associated with swing motion bolsters, transverse anchor links are fitted between the bolster beam and spring beam. This arrangement is very much lighter than the orthodox beam yet has the advantage that it does not induce compound stresses in the bolster springs when the bolster moves transversely.

To obviate normal friction plates in the swing bolster, the longitudinal forces from traction thrust and braking are transmitted by two links fitted

between the bogie frame and bolster. To cater for the compounded movements the links are fitted with ' Spherilastic ' rubber bonded bushes at each end.

The bogie side frames, transoms and headstocks are of fabricated box section construction to provide high bending and torsional stiffness. The bogie frames are stress-relieved.

The axleboxes are fitted with ' S.K.F.' single-row self-aligning spherical bearings. A short equalising spring beam is pin-joined to the underside of the axlebox and the primary coil springs rest in cups attached to the beam. Hydraulic dampers are fitted inside the springs. The primary and secondary springs are manufacturered from centreless ground silico-manganese steel bars which are crack detected before and after coiling and finished by shot blasting and zinc coating.

The wheels are 48 in. dia. on tread, the wheel centres being steel castings with elliptical shaped spokes and triangulated hubs and rims. The wheel sets are statically and dynamically balanced. All wheels are fitted with clasp type brakes. An individual brake cylinder is provided at each wheel and operates on the blocks by a system of levers and rods. A mechanically operated automatic slack adjuster is incorporated which permits full brake shoe wear without intermediate adjustment.

Earthing brushes are fitted on one end of each axle with connections to the bogie frame and superstructure.

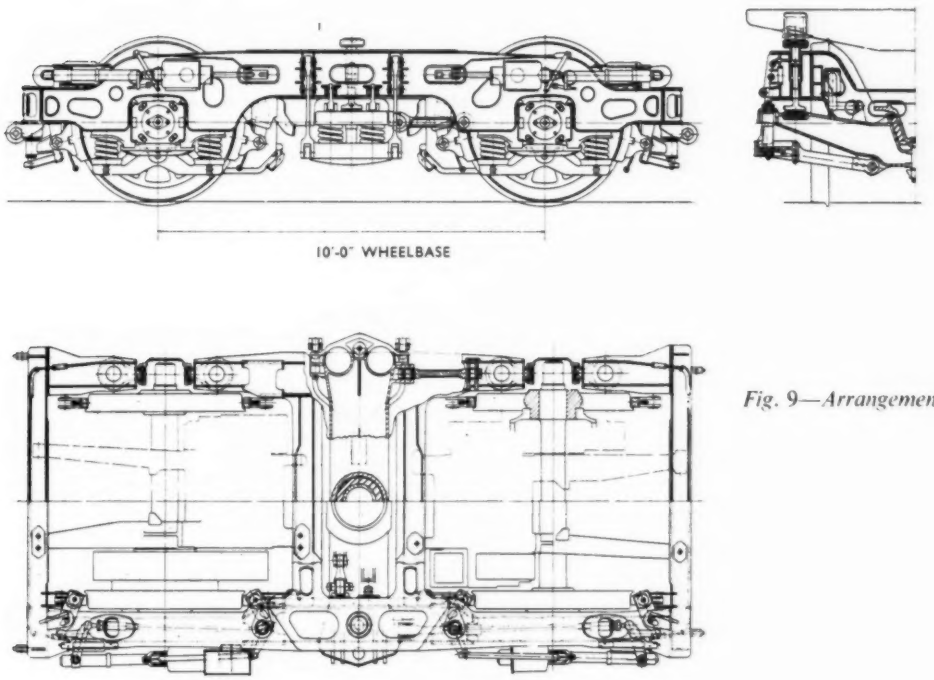


Fig. 9—Arrangement of the bogie

Frame and body structure

The frame and body (Fig. 10) is designed and fabricated as a unit stress bearing structure in ' Cor-Ten ' steel. The base is of shallow cellular construction with close spaced light gauge longitudinal and transverse members interlocked with each other. The structure is plated top and bottom to form a closed cell ; high vertical, longitudinal and torsional rigidity is thus obtained.

Fig. 10—*Locomotives in various stages of erection*

To obviate corrosion the interior of the structure is metal sprayed and adequately drained and vented.

The body side frames are of girder design. The vertical pillars are rectangular tubes and the cantrail a compound closed section. Combined with the base structure, cabs and bulkheads a comprehensive structural member of immense strength, yet light in weight, is achieved commensurate with the loads imposed.

As the roof can be completely open between cab bulkheads—to permit installation of the electrical equipment—no permanent structural ties can be provided, therefore to provide maximum torsional rigidity and prevent flexing of the body sides the side frames have both interior and exterior skins.

The exterior of the locomotive is made as flush as possible, devoid of such items as mouldings, to improve appearance but also to aid in obviating corrosion.

The aim has been to provide a structure which should be relatively trouble free throughout the life of the locomotive.

Resin bonded glass-fibre construction is used for the entire driving desk and for the side-entrance doors, cable ducts and covers. Considerable weight saving has resulted from this construction ; in addition, the general appearance is improved.

Brake system

These locomotives are equipped with the ' Metcalfe-Oerlikon ' vacuum controlled air brake and anti-wheel-slip apparatus.

THE COMPLETION of these locomotives shows that it is feasible to build, within the difficult loading gauge of British Railways, dual-voltage 3,000 hp. locomotives of low weight, whilst still retaining the ample margins and robust construction necessary for reliable operation.

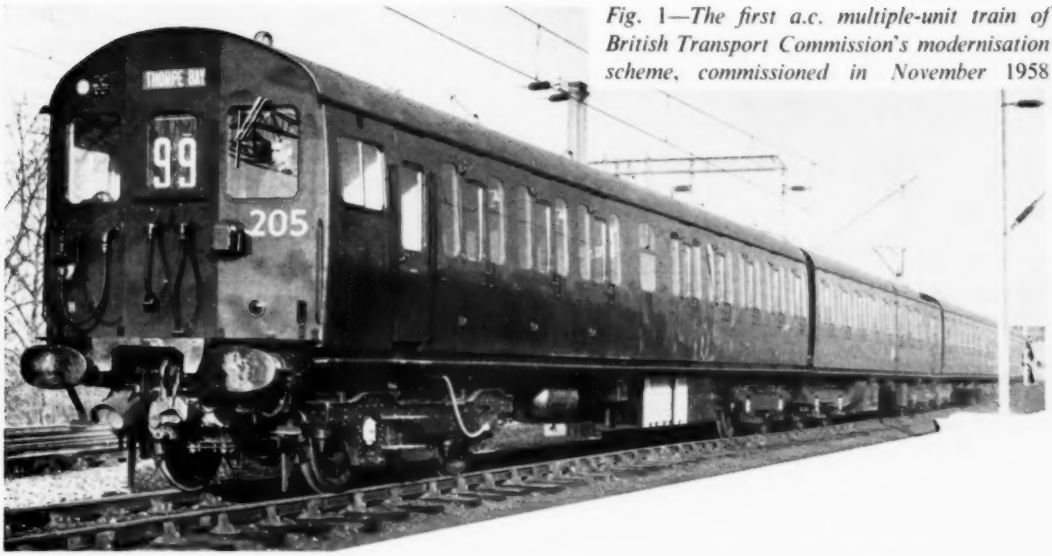


Fig. 1—The first a.c. multiple-unit train of British Transport Commission's modernisation scheme, commissioned in November 1958

IV—MULTIPLE-UNIT TRAIN EQUIPMENTS FOR BRITISH RAILWAYS

H. B. CALVERLEY, B.Sc.(Eng.), M.I.E.E., Assistant Chief Engineer (Development), Traction Department
E. WILLIAMS, B.Sc.(Eng.), A.M.I.E.E., Traction Control Design Department

THESE UNITS *went into public service on the Colchester-Clacton-Walton line in March 1959.*

IN JANUARY 1957 the British Transport Commission ordered 112 sets of equipment from the Company for multiple-unit stock. Each unit consists of four cars of which one is a motor-coach with four motors. The stock is intended for eventual use on the London-Tilbury-Southend line ; it has operated a public service on the Colchester-Clacton-Walton line since March 1959, and on the London-Shenfield and Southend line since October 1960. These services include both semi-fast and suburban duties. Higher performance on either type of duty can be obtained by removing the non-driving trailer and operating as a three-car unit.

Two or three units can be operated in multiple. The equipments can also multiple with those of other manufacturers. The coaches were designed and built by British Railways at Doncaster and York.

Leading particulars

The leading particulars, based on a four-car unit (Fig. 1), a line voltage of 22·5 kV, 100% secondary tappings and half-worn wheels, are as follows. (Sixteen passengers are taken as 1 ton.)

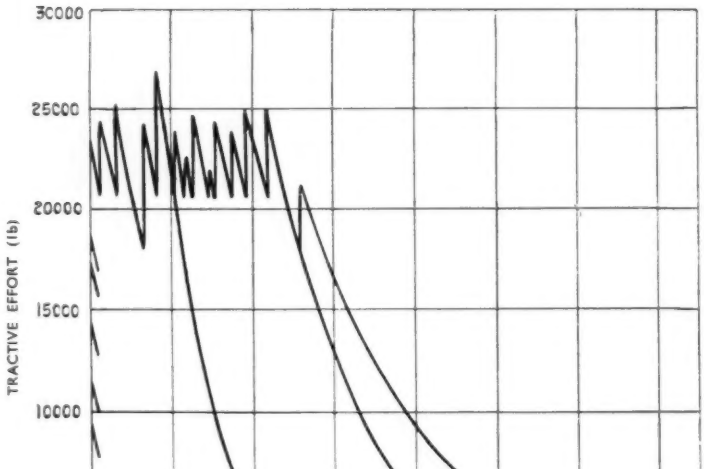
Vehicle	Unladen weight	Laden weight (all seats occupied)
Battery driving trailer	35·8 tons	40·8 tons
Motor coach	54·4 ,,	60·4 ,,
Non-driving trailer	30·5 ,,	35·5 ,,
Driving trailer	32·1 ,,	38·9 ,,
Total	152·8 tons	175·6 tons

Maximum axle load = 15·3 tons
,, service speed = 75 m.p.h.
Balancing speed on level tangent track = 67 m.p.h.

Acceleration on level tangent track		1·1 m.p.h./sec.
Average accelerating tractive effort		22,100 lb.
Continuous rating at wheel in weak field	Tractive effort	6,000 lb.
	Speed	48 m.p.h.
	Power	770 hp.
Total weight of electrical equipment		21·1 tons

The performance curve for the equipment under the above conditions is shown in Fig. 2.

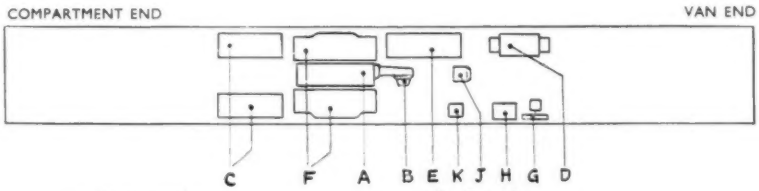
Additional tappings are provided on the secondary windings to give approximately 5% increase in voltage if required, i.e. 105%.



(1) (2) (3) (4) Running notches
R Train resistance (laden) on level tangent track
C Continuous rating

Fig. 2—Performance curves for one four-car unit based on 22·5 kV line voltage, 100% secondary tappings, and half-worn wheels

The main transformer and the traction power equipment are mounted under the motor-coach underframe, as shown in Fig. 3. All other items of h.v. equipment are mounted on the motor-coach roof above the guard's compartment. The main compressor, battery and battery charger are mounted under the underframe of the battery



A Main transformer
B Supply changeover switch
C Tap changer
D Reactors
E D.C. equipment
F Rectifier
G Transformer oil radiator
H Oil pump
J Brake cylinder
K Electro-pneumatic brake unit

Fig. 3—Layout of equipment on motor-coach underframe

driving trailer. The positioning of items of equipment has been influenced by consideration of weight distribution between axles.

Description of circuits

Power circuits

The power circuits are shown in Fig. 4. Current passes from the pantograph through the air-blast circuit breaker to the supply changeover switch on the main transformer. The switch operates off load, and connects the four sections of the primary winding in series (for 25 kV operation) or in parallel (for 6·25 kV operation). The return path to the rails is through an insulated brush box on each traction motor.

Each phase of the bi-phase secondary winding of the transformer consists of two

portions—one with tappings and one without. The tapped portions are used twice during notching—firstly in series with the reactors and secondly in series with the untapped portions. The change of connections is effected by the winding grouping switch, which does not make or break current ; the supply to the traction motors is not interrupted.

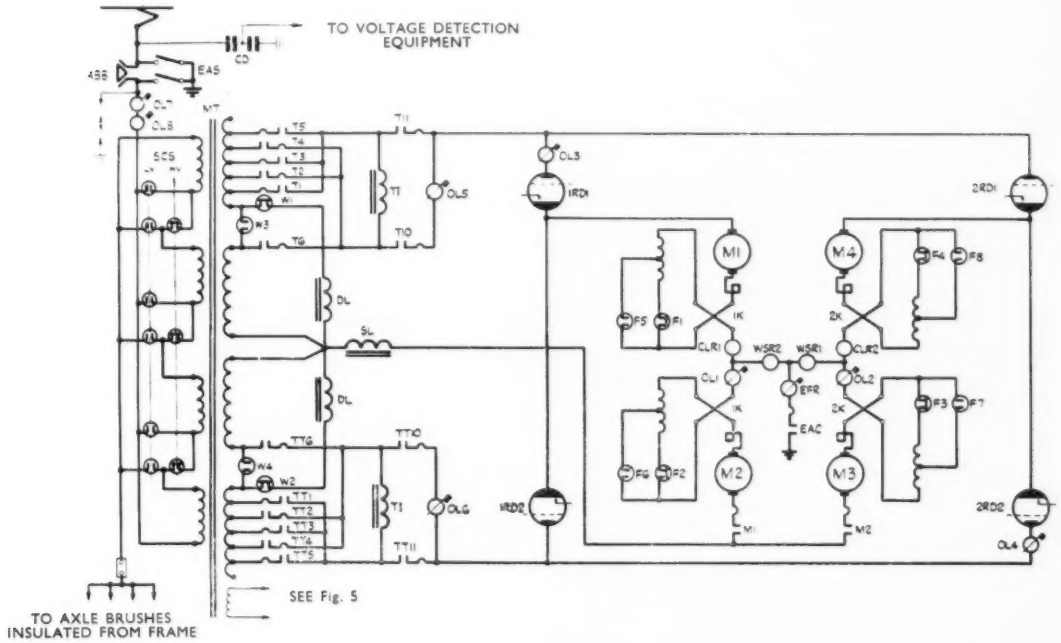
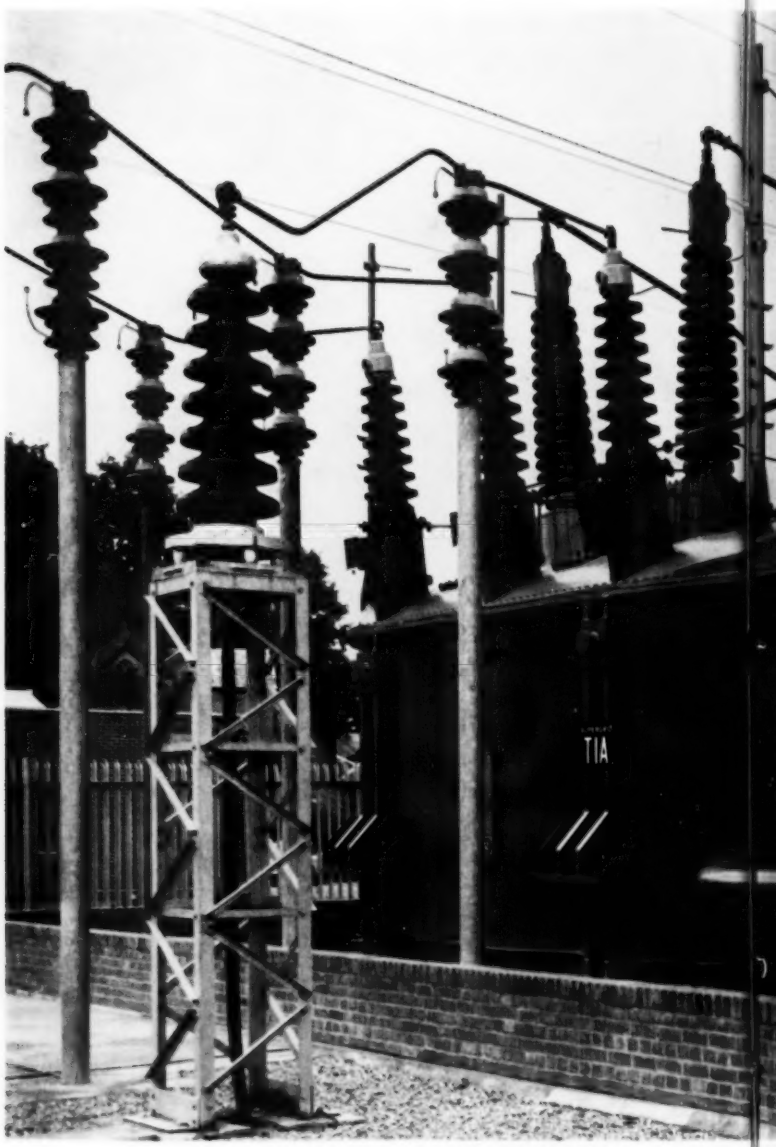


ABB	Air-blast circuit breaker
CD	Capacitive divider
CLR	Current limit relay
DL	Dropping reactor
EAC	Earth contactor
EAS	Earthing switch
EFR	Earth fault relay
F	Field tap switch
K	Reverser
(M)	Traction motor
M	Motor contactor
MT	Main transformer
OL1, 2	D.C. overload relay
OL3, 4	Anode overload relay
OL5, 6	Secondary overload relay
OL7, 8	Primary overload relay
RD	Main rectifier
SCS	Supply changeover switch
SL	Smoothing reactor
T, TT	Tap-changing contactor
TI	Tap-changing reactor
W	Winding grouping switch
WSR	Wheelslip relay

Fig. 4—Schematic diagram of power circuits, and notching sequence chart



A 120 MVA 275 132 kV 'English Electric' auto-tra
Generating Board at Iver substation, Buckinghamshire. T
it is fitted is designed to operate on system voltage u
changer will give service for twenty-five years witho

o-transformer, recently installed for the Central Electricity hire. The high-speed on-load resistor tap-changer with which tage up to 500 kV and currents up to 1000 A. This tap- ithout any maintenance to the contacts or the mechanism.

On-load tap-changing is performed by contactors in conjunction with reactors which are left in circuit on alternate notches to give pseudo-mid-tappings. On the lower notches the inherent voltage regulation of the transformer is low, hence additional reactance is provided to reduce the number of notches to a practicable value. Reactors rather than resistors were chosen to keep the starting losses low.

The decision to use contactors instead of a camshaft for tap-changing was influenced by the fact that notching back was not required ; electrical interlocking is therefore not difficult.

The tap-changer feeds two pairs of excitrons, each pair connected bi-phase. Bi-phase connection was chosen rather than bridge so that the output voltage is the minimum possible, consistent with operating the rectifiers at a high peak-inverse voltage. The use of a high peak-inverse voltage is necessary to obtain the required power output from the four rectifiers.

The rectifier output voltage was considered to be too high for optimum motor design ; the traction motors are therefore connected two in series. Weak-field operation is obtained by tapping rather than by diverting the field, in order to reduce the risk of flashover without resorting to inductive shunts. The field is not provided with a ripple divert, since it was possible within the chosen frame size to allow for the additional field losses due to ripple, and commutation is excellent without the divert.

The two motor strings are connected through a common smoothing reactor to the centre point of the secondary winding. The centre points of the strings are connected by a low-impedance equalising connection, whereby the behaviour of the motors under wheel-slip conditions approximates to that of parallel-connected motors. The equalising connection contains two wheel-slip relays with different settings, and is earthed through a low-impedance earth-fault relay and an earthing contactor. Earthing at this point, rather than at the d.c. negative lead, reduces the voltage to earth of the d.c. circuit.

Motors may be cut out in pairs. A control switch de-energises the coil of the appropriate motor contactor and the excitation of the appropriate excitrons, which then act as isolators.

Auxiliary circuits

Auxiliary circuits are shown in Fig. 5. The tertiary winding of the main transformer supplies heating and auxiliary circuits throughout the unit. Most of the machines are capacitor-start-and-run, with no switching between the starting and running conditions ; this arrangement was chosen because of its simplicity. The main compressor motor is series-wound and is fed via rectifiers ; this was considered the best way of obtaining, over the wide range of tertiary voltage, the high starting torque necessary. The battery charger is the static type, chosen for its simplicity compared with a motor-generator set and voltage regulator.

The battery charger and battery, in parallel, supply lighting throughout the unit, the auxiliary compressor motor on the unit, and control supplies throughout the train. The auxiliary compressor motor operates initially from the battery to provide air for raising the pantograph and closing the air-blast circuit breaker.

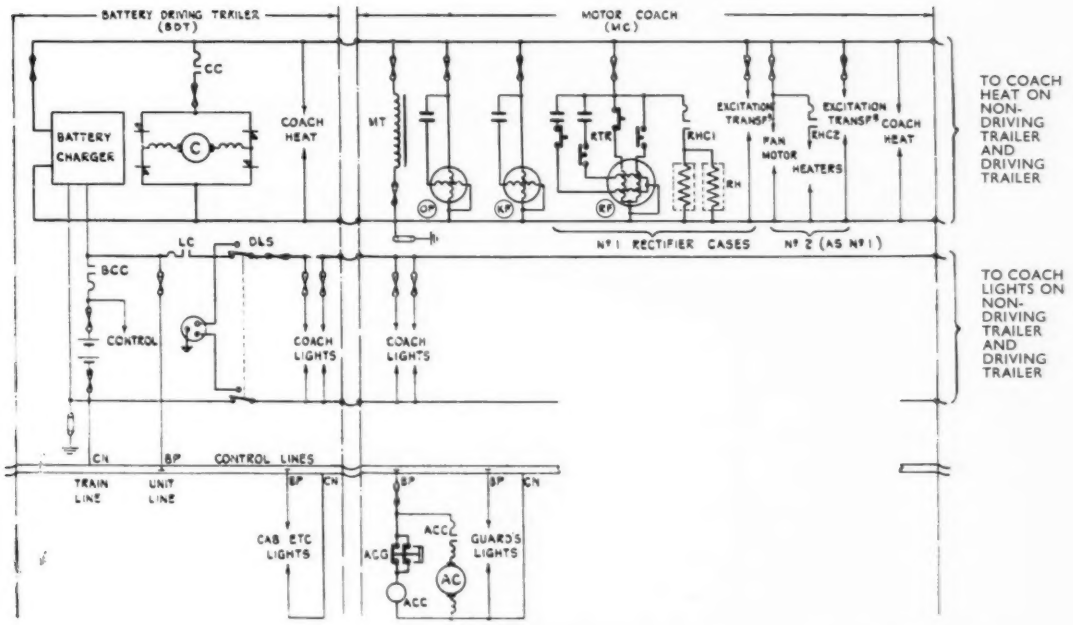
Description of electrical apparatus

H.V. equipment

The air-blast circuit breaker and the pantograph are of Brown Boveri and Stone-Faiveley manufacture, respectively.

A roof-mounted capacitor provides a feed to voltage detecting relays.

The h.v. current is taken through the guard's compartment by means of a long condenser bushing and then along the underframe to the transformer through a screened rubber-insulated cable. Above the roof the bushing is enclosed in an oil-filled shedded porcelain insulator ; the bottom end of the bushing and one cable termination are housed in an oil-filled junction box. The other cable termination is inside the main transformer. This arrangement facilitates erection, by allowing the entire cable to be installed before the bodywork is fitted.



(AC) Auxiliary compressor motor
ACC Auxiliary compressor contactor
ACG Auxiliary compressor governor
BCC Battery contactor
(C) Main compressor motor
CC Main compressor contactor
DLS Depot lighting changeover switch
(KF) Radiator fan motor
LC Lighting contactor
MT Main transformer
(OP) Oil pump motor
(RF) Rectifier fan motor
RH Rectifier heater
RHC Rectifier heater contactor
RTR Rectifier temperature control relay

Fig. 5—Schematic diagram of auxiliary circuits

The 25/6·25 kV changeover switch is electro-pneumatically operated and all its h.v. parts are oil immersed. It is mounted on an extension of the transformer tank which also houses the h.v. cable termination.

Main transformer

The following data applies to the 105% secondary tappings (ratings to I.E.C. 77) :—

Winding	Primary	Secondary	Tertiary
No. of phases . .	1	2	1
Rated voltage . .	25/6·25 kV	1875+1875V	284V
Rated kVA . .	990	1400	105
		Mean kVA 1195	

The transformer (Fig. 6) is of shell-type construction ; the core is of grain-oriented steel laminations built in two parts, and all joints are interleaved.

The windings consist of rectangular conductors wound in flat coils on a circular former. Primary and secondary coils are arranged in interleaved groups, and spacers between the coils form oil ducts. The insulation is Class A.

Except for the primary connections, all electrical connections are brought out through copper strips moulded into epoxy-resin terminal blocks. This saves space and reduces the number of gaskets compared with separate porcelain insulators.

The cooling oil is circulated through the transformer and the reactor tank to a radiator by a glandless centrifugal pump. The radiator is cooled by air blast. A separate conservator is mounted in the guard's compartment.

Without disturbing the pipework, the oil can be reconditioned by passing it through an

external filtration and heating unit.

Control gear

The tap-changer is housed in two cases, one of which is shown in Fig. 7. The tapping contactors are electro-pneumatically operated, single pole, and have a laminated magnetic circuit incorporated in the series-wound blow-out system. The auxiliary contacts, mounted at the front, are the cam-operated silver type. The magnet valve, mounted beneath the auxiliary contacts, is the rubber-seating type which does not need grinding in ; the coil is potted in epoxy-resin.

The winding grouping switch is an electro-pneumatically operated, two-position camshaft ; it has four sets of silver-butt main contacts, and cam-operated silver auxiliary contacts.

The tap-changing equipment is provided with full sequence and protective-interlocking by a single time-delay relay and the auxiliary contacts already referred to.

The master controller is shown in Fig. 9.

Rectifiers

The rectifiers are air-cooled excitrons of the sealed steel-tank type. They are of an improved design, based on the type which was fitted in 1955 to a train on the Lancaster-Morecambe-Heysham line. Each is provided with an ignition/excitation anode and a de-ionising grid. The ignition device consists of a solenoid and floating plunger, which causes a jet of mercury from the cathode to impinge on the ignition anode. The cathode plate has cooling fins, and the cylindrical portion of the tank has wire cooling coils brazed to it ; these are surrounded by a cylindrical shroud.

The continuous rating of a pair of excitrons in bi-phase is 250A d.c. at 1,240V d.c., and 35°C ambient temperature. The type tests included repeated loadings at 560A for 40 sec., immediately following load at the continuous rating, and also a cold starting test by applying a load of 560A for 40 sec. immediately after the heaters had brought the rectifiers up to the minimum operating temperature from −12°C. The arrangement of one pair, with their auxiliaries, is shown in Fig. 8.

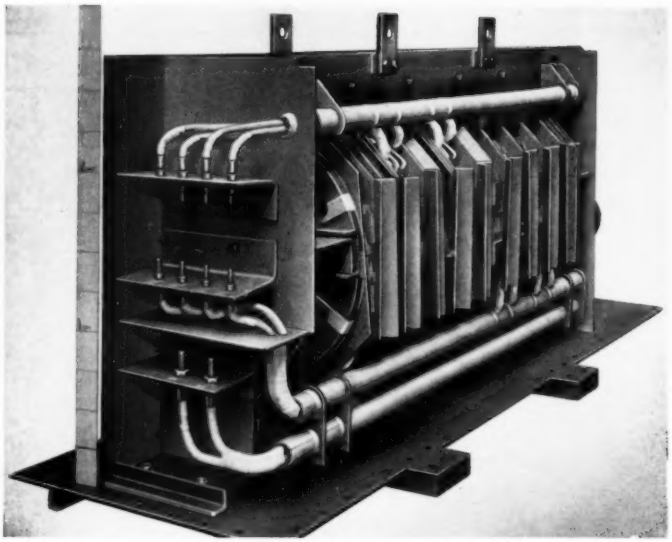


Fig. 6—The core and windings of the main transformer, designed for under-car mounting

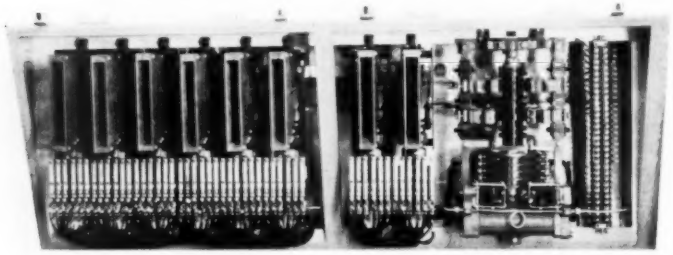


Fig. 7—Covers removed to show the layout in one of the tap changer cases. The winding grouping switch is on the right

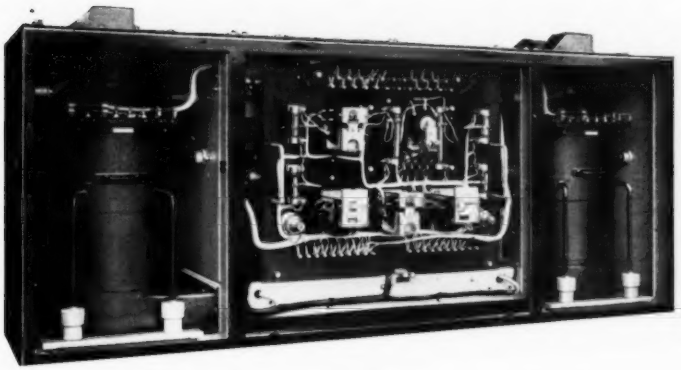


Fig. 8—Case for under-car mounting containing two single-anode mercury-arc rectifiers

All the contents are accessible and removable from the front or bottom.

Air from under the floor enters through a grilled opening in the back wall of the case. A fibreglass duct leads the air over a vertically-mounted fan motor to a centrifugal fan mounted in the centre of a steel duct in the floor of the case and provided with dirt-extracting vanes. Each branch of the duct contains air heaters and is connected to a moulded rubber duct which surrounds the cathode of the excitron. The air passes upwards over the cooling coils and leaves the case through a louvred front cover.

The rectifier cooling fan runs at slow speed when the heaters are on and delivers 400 c.f.m. of hot air but, when the heaters are switched off by the thermostats, it runs at high speed to deliver 1,200 c.f.m. of cooling air.

Each excitron is resiliently-mounted from insulators secured to a tray. The tray carries a complete replaceable sub-assembly, and can be slid in and out of the case.

Reactors

All three reactors are oil cooled and are mounted in a common tank. The smoothing reactor has a continuous rating matched to that of the transformer; it has an inductance of approximately 5 mH at 500A d.c. The other reactors are short-time rated since they are not in circuit on running notches.

All connections are brought out through copper strips moulded into epoxy-resin terminal blocks.

Traction motors

The traction motors are axle hung, self-ventilated, four-pole series-wound d.c. machines. They are continuously rated at 192 h.p. (620 V 250 A) when in weak field and carrying undulating current. This rating corresponds to a line voltage of 22·5 kV. The permissible temperature rises of the armature and fields are 120°C and 130°C respectively.

A fan at the pinion end draws cooling air from the vicinity of the motor carcase through a screen into the commutator end. The screen removes the larger particles of dirt. This arrangement avoids the use of flexible bellows.

The motors operate very satisfactorily with a large ripple in their current, approximately 40%. A weak field running notch is obtained by a field

Fig. 9—The master controller

TABLE I

No. off	Function	Output	Supply	Rating (hp.)	Speed (r.p.m.)
1	Auxiliary compressor ..	3 c.f.m.(f.a.d.)	110V d.c.	1·5	—
1	Main compressor	23 c.f.m.(f.a.d.)	200V d.c.	6·5	—
2	Rectifier cooling fans ..	1,200 c.f.m.	240V a.c.	0·75/·03	1,470/490
1	Oil circulating pump ..	80 g.p.m.	240V a.c.	1·5	1,425
1	Oil cooling fan	4,750 c.f.m.	240V a.c.	1·5	1,450

tapping and no field diverts or laminated magnetic yoke are used.

The armature is lap wound, in order to obtain the required power output from the smallest motor, and to contribute to good commutation.

Auxiliaries

With the exception of the compressor motors, which are d.c., all auxiliary machines are capacitor start-and-run induction motors. These machines are detailed in Table 1.

The main and auxiliary compressors are of Westinghouse Brake and Signal Company manufacture. The battery charger, by the same company, gives 110 V d.c. transductor-regulated output for lighting, control and charging the 80 A.H. Nife nickel-cadmium alkaline battery.

Protection

The equipment is protected from line voltage surges by a double rod gap fitted to the porcelain insulator of the h.v. bushing and set to have a 50% flashover at 135 kV peak.

Tripping of the air-blast circuit breaker occurs under the following conditions : overcurrent in the h.v. lead-in (setting 600 A on 6·25 kV or 200 A on 25 kV) ; overcurrent in the tap-changer circuit ; low oil-level in the transformer ; rectifier backfires ; traction motor overcurrent ; and an earth-fault in the transformer secondary, or tap-changer, or d.c. power circuits.

Rectifier under-temperature and over-temperature thermostats remove load from the rectifiers unless the temperature is within the working range.

Operation of protection relays lights a fault indicator lamp in the guard's van and each relay has an indicator flag to assist in locating faults.

Operation of one wheel-slip relay halts the tap-changing progression ; if the slip stops, the relay resets and progression continues. If slip is more severe the second relay operates and cuts power off ; the relay then resets and progression recommences.

Regeneration via an earth fault when towing a 'dead' unit is prevented by the earthing contactor which is open whenever the unit is shut down. This contactor and one motor contactor must be closed before the air-blast circuit breaker can close.

SATISFACTORY PERFORMANCE of the equipments since the first of these units was commissioned in December 1958 has justfied the choice of circuitry and the design of apparatus. An order has been received for a further forty-two equipments, which are identical except that silicon rectifiers are substituted for the mercury-arc rectifiers. The first of these latter units was commissioned in February 1961.

V—THE FIRST 50 C/S EQUIPMENT WITH NOTCHLESS ACCELERATION

E. A. K. JARVIS, B.Sc.(Eng.), A.M.I.E.E., Traction Development Department

THE BRITISH TRANSFORT COMMISSION consented to the installation of an experimental equipment in the last of the 112 motor coaches of the London-Tilbury-Southend rolling stock described in Section IV. It was decided to incorporate four new major items: silicon rectifiers mounted undercar; notchless acceleration by an inter-step regulating transformer; constant-current control by a magnetic amplifier; and an air-cooled main smoothing reactor with Class H insulation. Detailed design work commenced in January 1959, and delivery to the erection site was effected twelve months later. Although it can be claimed that the entire conception was an advanced one, the rate of development in the art of 50 c/s traction in several countries is so rapid that some of the equipment might already be considered out-dated. The entire development, however, represents an important step into new realms, enabling valuable experience to be gained on the test-bed and on the track.

Space does not permit discussion of layout or mechanical problems, including those of the air cooling of silicon rectifiers. The following paragraphs are therefore mainly devoted to describing the circuits and discussing the questions which influenced the choice of circuits.

Only those features which are different from the conventional circuits of the London-Tilbury-Southend rolling stock will be touched upon.

Rectifiers

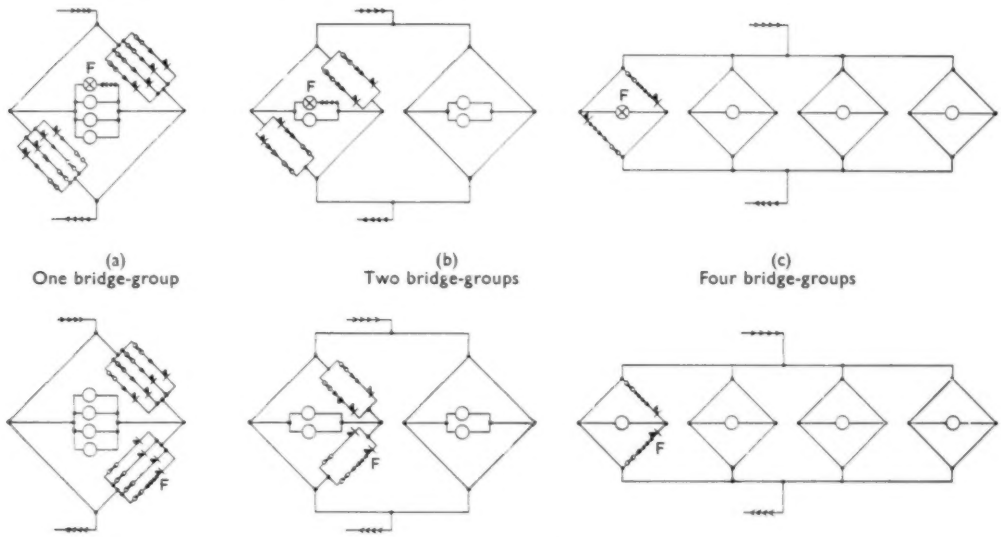
The use of silicon cells makes it possible to reap the advantages of using a bridge circuit, but with none of the disadvantages which apply when using mercury-arc rectifiers with a bridge circuit. Fig. 3 shows the complete coach-set of rectifiers.

The main circuit breaker controlling the input to the rectifier transformer is usually a moderately high-speed type (80–100 m.sec. including relay time) but this is not fast enough to protect the silicon cells against maximum intensity fault currents. Additional protection must therefore be provided either by an ultra-high-speed short-circuiter connected across the extremities of the secondary winding or by special fuses in the a.c. part of the rectifier bridges. Whichever method is used, the current per cell due to a d.c. short-circuit (see the upper half of Fig. 1), is least when the largest number of parallel-connected cells in any one bridge-group is used, i.e. arrangement (a) is the best and arrangement (c) is the worst. As regards rectifier faults (always short-circuits), overcurrent only occurs after a complete series-string of rectifiers has been destroyed and the object of the protection is to prevent damage to the cells in the healthy arm in series opposition to the arm in which the failure has occurred. The lower half of Fig. 1 shows that, again, the current-per-cell in the healthy arm is least when the largest number of parallel-connected cells in any one bridge-group are used i.e. again (a) is best and (c) is worst.

Further consideration of rectifier protection is confined to the technique of using fuses, as this is the method used on this coach. The main problem is to ensure discrimination, so that when a motor flashes over, the main circuit breaker trips before any fuse blows, but yet when a rectifier fault occurs (assumed very rare) one fuse only blows extremely rapidly and before the main circuit breaker responds. Because the magnitude of fault current due to a rectifier fault might be not appreciably greater than that due to motor flash-over, the usual inverse-time characteristic of the fuse is not suitable to ensure discrimination. It is therefore necessary to use circuits which 'channel' less current through the fuse in the case of motor flash-over than in the case of rectifier fault. This is best achieved by the single bridge-group feeding all the motors as in (a) which, if four fuses are used in parallel per arm, results in four times as much current in the fuse which is to blow as in those which should not blow, i.e. a discrimination factor of 1/4.

Fuses are exceedingly versatile in that, although their first cost is relatively small, they provide

PATH OF d.c. SHORT-CIRCUIT CURRENTS (IMMEDIATELY BELOW)



(a) One bridge-group

(b) Two bridge-groups

(c) Four bridge-groups

PATH OF RECTIFIER SHORT-CIRCUIT CURRENTS (IMMEDIATELY ABOVE)

(i) The magnitude of the short-circuit current is assumed to be the same for the d.c. fault and for the rectifier fault.
(ii) The magnitude of the short-circuit current is represented by four arrows thus →→→→.
(iii) All the bridge arms for any one diagram are identically equipped, but for simplicity only the arms carrying short-circuit current are shown complete with rectifiers and fuses.
(iv) Each diagram represents the conditions for one half-cycle.
(v) Each single rectifier represents several rectifiers connected in series.
(vi) The position of the short-circuit is denoted by the letter 'F'.

Fig. 1—Comparison of various circuits of rectifiers and motors

detection of, protection against, isolation of, and indication of a fault.

Referring to Fig. 2, it will be noted that the fuses are connected in the a.c. terminals of each bridge rather than in each arm. This does not affect the principle of the discussion above. It will be noted that a single bridge group feeding all four motors is used and that four fuses in parallel are used, giving an excellent discrimination factor of 1/4. If one fuse blows, the current-balance relay CBR operates to cut-out two of the four motors. It functions by reason of the fact that if any one fuse blows, the dis-equilibrium of current through some of the remaining fuses provides a difference effect in the two busbars which link the core of the relay equal to 16.7% of the total d.c. current.

D.C. circuits

The traction motors are connected in parallel across the d.c. output of the rectifiers which means that if a wheel slips, the voltage across the motor affected is not increased as it would be if two or more motors were connected in series. Any tendency to excessive 'slip-r.p.m.' is thus avoided.

The parallel connection of all four motors means that some parts of the circuit carry the total current of all four motors. This represents more current than hitherto normal for motor-coaches and makes it difficult to pass the cables in the available space. Butyl rubber cables designed for a copper temperature of 85°C. at their continuous rating are therefore employed.

For smoothing the traction motor current, an air-cooled reactor (Class H insulated) is used, in which the insulated coils are in direct contact with air movement beneath the coach caused by the velocity of the train. By this means, the

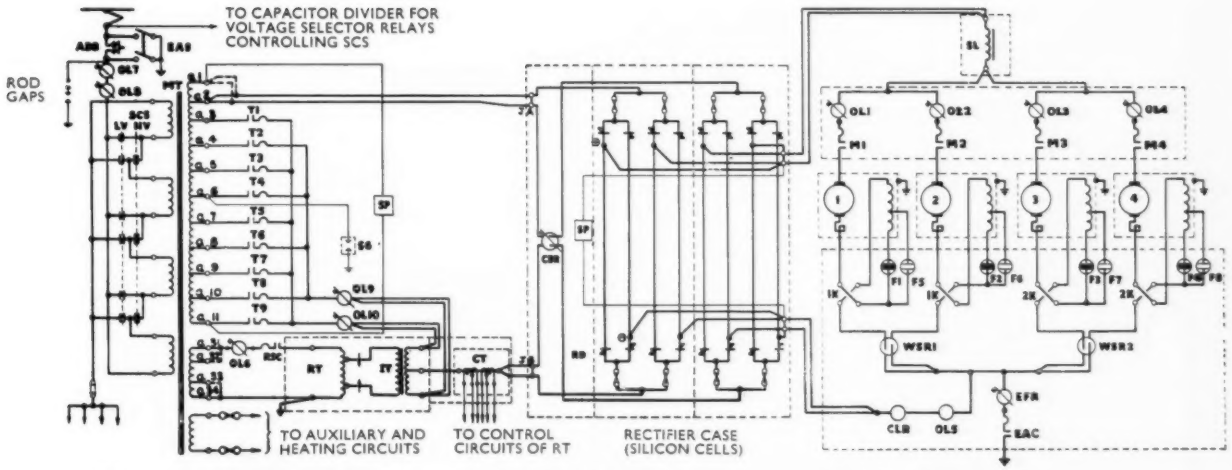

TO CAPACITOR DIVIDER FOR VOLTAGE SELECTOR RELAYS CONTROLLING SCS
ROD GAPS
TO AUXILIARY AND HEATING CIRCUITS
TO CONTROL CIRCUITS OF RT
RECTIFIER CASE (SILICON CELLS)

ABB	Air blast circuit breaker	IT	Injection transformer	RD	Main rectifier
CBR	Rectifier current balance relay	M1-4	Motor contactor	RSC	Regulator supply contactor
CLR	Current limit relay	MT	Main transformer	RT	Regulating transformer
CT	Secondary current transformer	OL1-4	D.C. overload relay	SP	Surge protection
EAC	Earthing contactor	OL5	D.C. overload relay	SCS	Supply changeover switch
EAS	Earthing switch	OL6	Regulator supply relay	SG	Spark gap
EFR	Earth fault relay	OL7	Primary overload relay	SL	Smoothing reactor
F1-8	Field tap switch	OL8	Primary overload relay	T1-9	Tapping contactor
1K, 2K	Reverser	OL9-10	Secondary overload relay	WSR1, 2	Wheel slip relay

Fig. 2—Schematic diagram of the power circuits

transformer becomes the only oil-cooled item and the oil pipe layout can be much more compact by being made integral with the transformer.

Notchless acceleration

The voltage applied to the traction motors is increased in a stepless manner using a regulating transformer as an inter-step device ; this was provided by Brentford Transformers Limited who acted in the closest collaboration with 'English Electric ' in the engineering of the notchless control scheme. The regulating transformer is an infinitely variable ratio auto-transformer and comprises, in essence, an edge-wound copper spiral surrounding a laminated core, the copper having been pre-insulated before winding by Class H insulation. The insulation is ground off in two fairly broad bands diametrically opposite one another and along the entire length of the coil, causing the top surface of the conductors to be disclosed in the form of two straight ' tracks '. An assembly of carbon rollers is in contact with each track and the rollers are moved along the tracks starting at opposite ends,

Fig. 3—The silicon rectifier unit, with one tray withdrawn

passing each other in the middle and going on to complete a traverse when each roller-assembly reaches the end opposite to that from which it started. One roller assembly and part of one track are shown in Fig. 4.

Referring to Fig. 2, a winding a31-a34 on the main transformer feeds the regulating transformer. The moving rollers (only two are shown in order to simplify the diagram) collect a voltage from the regulating transformer winding, varying in magnitude and polarity in accordance with the position of the rollers. This voltage is injected into the input circuit of the power (silicon) rectifiers by means of the centre-tapped winding of the injection transformer IT.

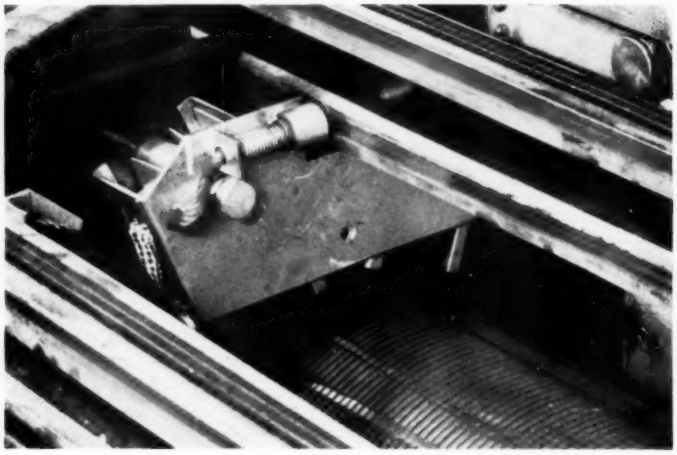


Fig. 4—Part of the regulating transformer winding, showing one set of rollers

The operation of the entire circuit will now be described from the position of zero voltage on the traction motors up to the point where contactor T2 is closed and the voltage on the motors corresponds to the mid-voltage between T2 and T3. The section a1-a2 of the main transformer can be ignored and it must be remembered that the voltage of the section a2-a3 is only a half-step, whereas that of each of the succeeding eight steps up to and including a10-a11 is a whole-step.

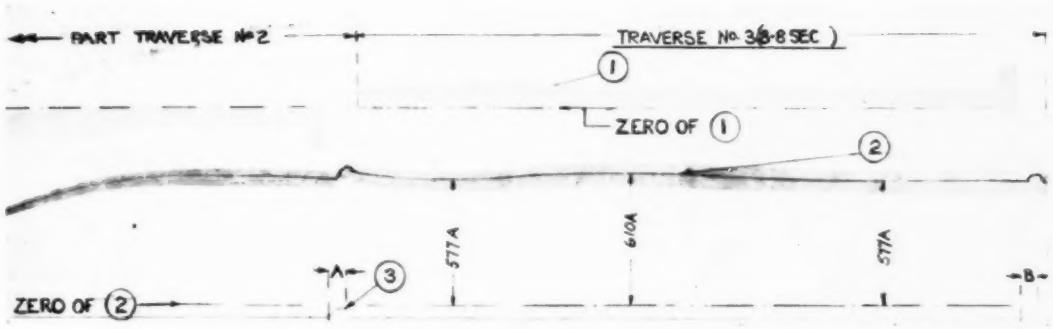
The first contactor to close is T1, thus bringing into use the half-step of voltage due to a2-a3. The voltage of one side of the centre-tapped winding of the injection transformer is, however, in series. At this stage the rollers are at the ends and give maximum 'buck' (half a step) so that the total output voltage across wires JA-JB is zero. As the rollers move, the amount of buck is reduced and then changed to 'boost' after they have passed one another. At the end of the first complete traverse, when the rollers have reached the opposite ends, the total voltage is that for a full step, i.e. half a step due to a2-a3, plus half a step of boost (or T1½ total).

The voltage across the contacts of T2 is zero at this stage when it is caused to close, thus connecting the extremities of the centre-tapped winding of IT across a3-a4. The voltage across wires JA-JB is still T1½ but obtained by auto-transformer action of the centre-tapped winding rather than by T1 + boost.

Contactor T1 now opens and the current flows through T2 alone, but the voltage across wires JA-JB is still T1½ but obtained in the form of T2 + buck i.e. sections a2-a4 minus the voltage of the appropriate half of the centre-tapped winding of IT. The bucking polarity is obtained without movement of the rollers because with T2 closed instead of T1 the opposite half of the centre-tapped transformer is brought into use. The rollers are then driven in the opposite direction until they have regained their original ends at the termination of their second traverse to give a voltage of T2½ in the form of T2 + boost. This process is repeated until eight traverses have been completed, by which time T8 and T9 are closed to provide the maximum voltage of T8½.

Each transition between the end of one traverse and the start of the next is completed in about one-third of a second.

In conformity with the policy of eliminating oil wherever possible, the regulating transformer case is filled with nitrogen at a slight positive pressure relative to atmosphere. The elimination of oil makes it possible to work up to the limits of



Trace (1) Voltage applied to regulator 'pilot' motor. This reverses polarity for each traverse. At the end of each traverse maximum voltage is applied for a short time.

Trace (2) Traction motor current in amperes. Cyclic mean values are marked.

Trace (3) Total current to contactor coils. The increased value at A and B shows when two coils are energised simultaneously.

The 'bands' are due to the waveform which could only be seen clearly if a much faster timebase were used.

Fig. 5—Oscillograph of notchless unit on level track, hauling eight cars

temperature permitted by Class H insulation, and thereby reduce weight.

Constant current control

Control of acceleration is obtained by varying the voltage applied to the small pilot motor driving the regulating transformer. This is effected by a self-excited magnetic amplifier which inserts varying impedance in the circuit of the pilot motor armature. The magnetic amplifier could be controlled in any desired manner e.g. to provide vehicle tractive effort varying in accordance with the maximum (different) values of adhesion practicable at various speeds. In this instance, however, the motor coach must operate in multiple with other conventional motor coaches and the magnetic amplifier is therefore arranged to vary the voltage across the pilot motor, and therefore its speed, in such a manner as to result in constant current in the traction motors. This necessitates a traverse of the regulating transformer rollers in about $2\frac{1}{2}$ sec. on level track, slower on 'up' grades, with a maximum time of about $7\frac{1}{2}$ sec. for the steepest up grade. If two traction motors are cut-out, the magnetic amplifier automatically controls to about half the normal total rectified current and some traverses as slow as 25 sec. or more are required and are obtained on steep up-grades.

If wheelslip occurs, or very slight traction motor overcurrent (e.g. due to sudden variation in line voltage), the relays WSR1, WSR2, or OL5, cause the regulator rollers to run back to the end from which they last set off. Prolonged wheelslip or appreciable traction motor over-current results in tripping of the air blast breaker.

THE COMBINATION OF NOTCHLESS CONTROL, parallel connection of all motors, and wheelslip protection, gives exceptionally good adhesion characteristics. The degree of constancy of traction motor current is shown by Fig. 5, which shows that throughout a traverse the current is almost perfectly constant. At each of the eight transitions (only two are shown) there is a slight short-duration increase in current but much less both as regards duration and magnitude than for each of the twenty-two notches of the conventional London-Tilbury-Southend equipment.

Another feature is that the arcing duty of the contactors is easier than for conventional equipments. This is because, for the purpose of tap-changing, the tapping contactors close and open with zero voltage across their contacts and because the magnitude of the circulating current while two contactors are closed is small, because the impedance presented by the injection transformer to circulating currents can be (and is) high.

VI—THE LATEST LOCOMOTIVE, USING TRANSDUCTOR CONTROL

G. W. GRAHAM, B.Sc.(Eng.), Traction Development Department

OF THE VARIOUS METHODS OF ACHIEVING the aims of notchless control and reduction of mechanical switchgear in rectifier traction equipment, one which has periodically attracted interest is that of the grid-controlled arc rectifier.

The simplest application is shown in Fig. 1a, in which a single stage of grid control covers the full voltage range. This is unacceptable in practice because of the poor power factor at part voltage and excessive harmonic interference with the supply.

R = Grid-controlled arc rectifier
M = Traction motor load circuit

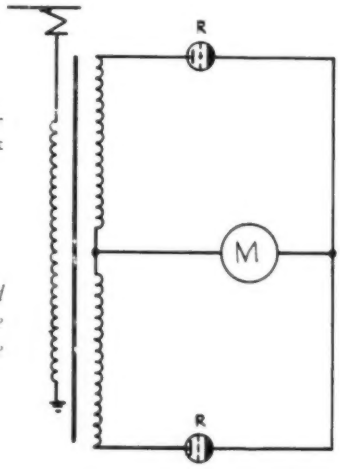


Fig. 1a—Grid-controlled rectifiers used to provide control of the total d.c. voltage

Fig. 1b shows an arrangement which could provide smooth voltage control with no tap-changing switchgear. By splitting the full voltage range into several grid-control stages, lower harmonic content and better power factor are obtained. In a sequence of increasing voltage, R_n would be allowed to fire free, giving load voltage corresponding to T_n. To raise the load voltage, R_{n-1} would be allowed to fire progressively earlier in the cycle. As R_{n-1} fires, R_n blocks as its cathode voltage exceeds its anode voltage. The voltage applied to the load is then somewhat as in Fig. 1c, (commutation effects being ignored). When R_{n-1} is firing free, R_{n-2} may be progressively un-blocked to increased load voltage to a value corresponding to T_{n-2}.

The arrangement is clearly uneconomical in rectifiers and a compromise is illustrated in Fig. 2a, where the same pair of rectifiers is used for each tap change sequence, being connected to the appropriate tappings by selector switches which do not have to rupture load. In an increasing voltage sequence, with tap selector switches T_1 and T_2 closed, R_O fires free and R_E is progressively un-blocked until the load voltage corresponds to T_2.

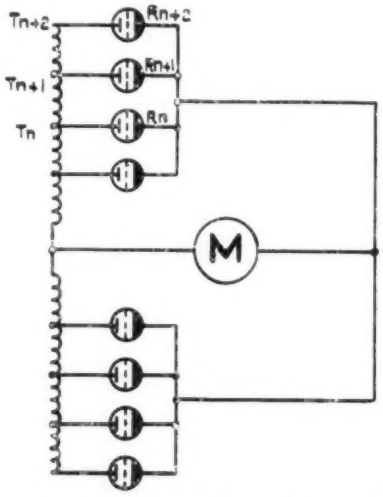


Fig. 1b—Grid-controlled rectifiers used to provide inter-tap control of d.c. voltage

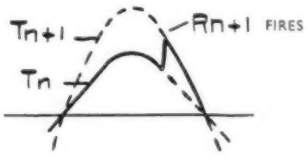


Fig. 1c—Simplified voltage waveform resulting from inter-tap grid-control

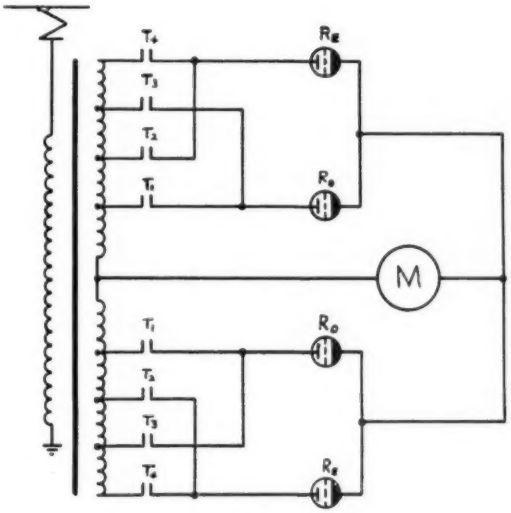


Fig. 2a—The use of mechanical switches to reduce the number of rectifiers

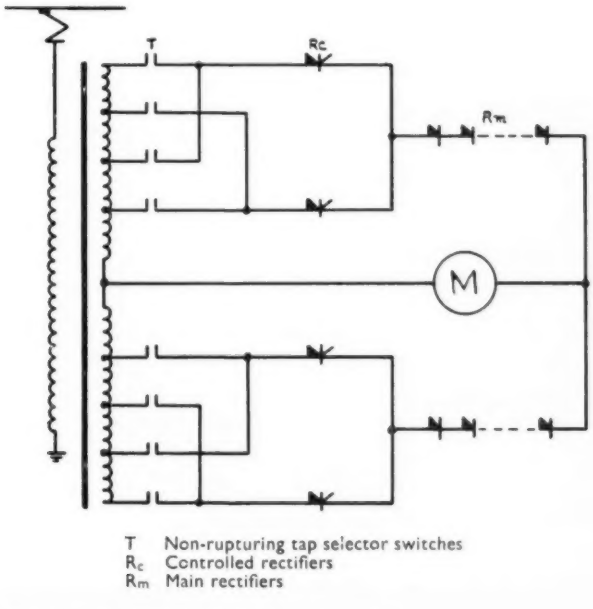


Fig. 2b—The application of semi-conductor rectifiers to the circuit of Fig. 2a

R_O is then fully blocked, and T_1 may be opened on no current, and T_3 closed without affecting load voltage. The sequence is then repeated. It is noteworthy that reduction of voltage and downward tap-changes are made by an exact reversal of the process. The rectifier connected to the higher tap is un-blocked successively later in the half-cycle until it does not conduct at all. It may then be switched to the next-but-one tap lower, and completely un-blocked prior to further reduction of voltage.

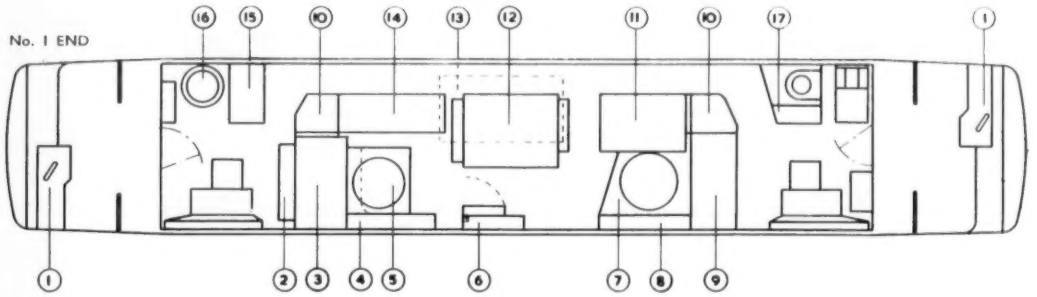
Even this scheme involves twice the number of rectifiers needed for the basic a.c./d.c. conversion. However, the advent of the semi-conductor rectifiers has rather modified the picture. The order of d.c. voltage established by optimum traction motor design requires the use of several cells in series, but, provided that the inverse voltage rating of a single cell is satisfactory for one inter-tap voltage, only the first cell in each rectifier string need be duplicated, and of the 'gated', or controlled, type. Such an arrangement is illustrated in Fig. 2b, and control is effected exactly as described above.

At the moment, silicon controlled diodes are not an economic proposition for this type of application. However, the circuit can be employed with other switching devices, and this article describes a particular application employing transductors as the switching elements.

Preliminary design and testing

In December 1958, the Company put in hand a design study based on the requirements of a motor-coach equipment, but the opportunity arose, by agreement with the British Transport Commission, to equip with silicon rectifiers and transductor-assisted tap-changing one of the a.c. locomotives under construction for the Commission.

A revised study was therefore made to determine the best type of transductor circuit for the application. It was then decided to conduct a test on a prototype equipment to obtain practical confirmation that the scheme was satisfactory before embarking on a full production equipment.



1 Driver's desk
2. Rectifier air reversing duct
3. Rectifier frame
4. Rectifier air inlet
5. Rectifier fan and motor
6. Transductor auxiliary equipment case
7. Oil radiator fan and motor
8. Oil radiator
9. Motor contactor frame
10. Reverser and field tap switches
11. Dynamic brake resistor
12. Main transformer
13. Transductors and smoothing inductors
14. Power and control camshaft frame
15. No. 1 auxiliary frame
16. Arno convertor
17. No. 2 auxiliary frame

Fig. 3—Layout of equipment

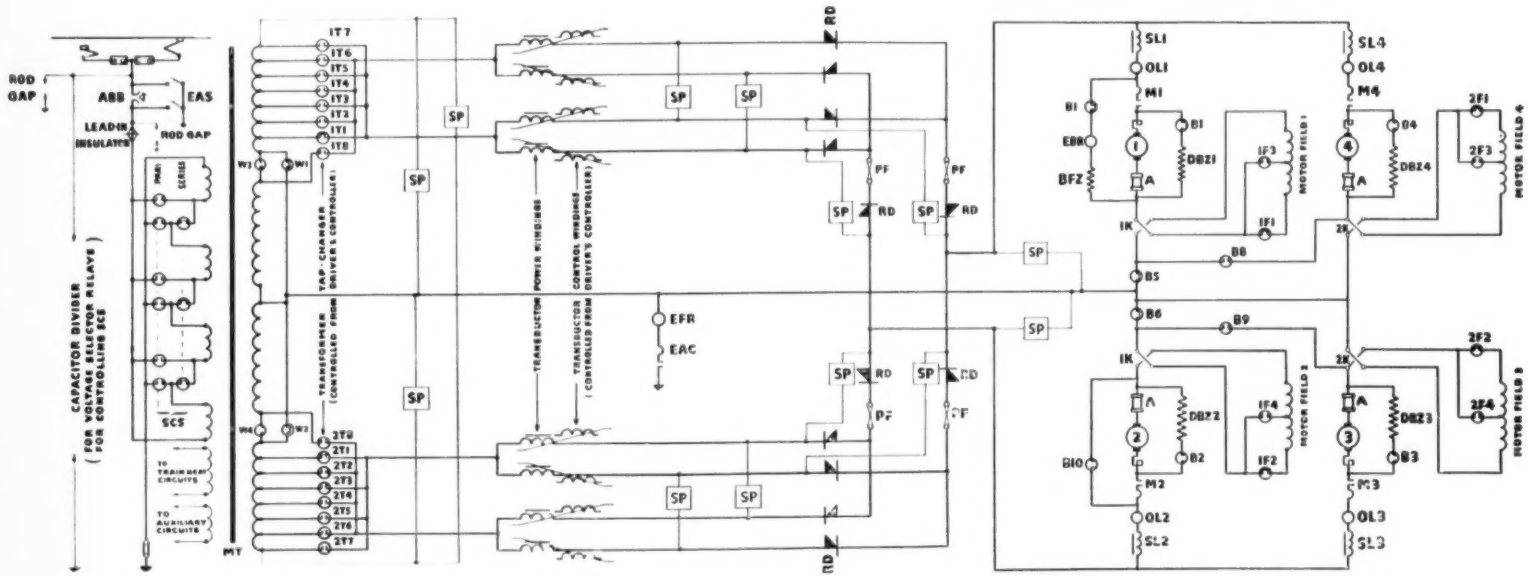


ABB	Air blast circuit breaker	EAS	Earthing switch	(1) (2) (3) (4)	Traction motors	RD	Main rectifier
A	Ammeter shunts (motor)	EBR	Emergency brake relay	M 1-4	Motor contactor	SCS	Supply changeover switch
B	Power/brake changeover switch	EFR	Earth fault relay	MT	Main transformer	SL 1-4	Smoothing reactor
BFZ	Brake field resistor	F	Electro-pneumatic field tap switches	OL 1-4	Overload relays	SP	Surge protection
DBZ 1-4	Dynamic brake resistor	K	Electro-pneumatic reverser switches	PF	Power fuses	T	Tap-changer contacts
EAC	Earthing contactor					W	Winding grouping switch

Fig. 4—Schematic diagram of the power circuits

For this purpose, a half locomotive set of equipment was assembled, using transductors with standard distribution transformer wound cores, and other contract and prototype items. It was demonstrated in June 1960 and showed itself capable of virtually spark-free tap changing at up to 2400A transformer secondary current.

This testing brought to light certain shortcomings in the surge protection arrangements previously envisaged, and these have been modified for the production equipment. Certain changes in the transductor characteristics were also decided upon.

General design of the locomotive

Meanwhile, design of the production equipment and its arrangement in the locomotive (Fig. 3) was proceeding. A main consideration was to reduce to the minimum alteration to the standard locomotives, particularly in respect of the mechanical parts.

The transductors

The first point to settle was clearly the location of the transductors. The smooth control of load voltage which transductors can provide renders unnecessary the voltage-dropping reactors employed on the ignitron locomotives to assist notching (see Section III). The inter-tap reactors are, of course, also no longer required. It appeared just possible that the transductors could occupy the very restricted space thus vacated in the reactor tank. Enlargement of this tank would have been extremely difficult owing to the location of oil pipes and cable ducts being intimately connected with underframe design. It was finally found possible to fit the units into the tank.

The rectifiers

The silicon rectifiers occupy about one-half the volume of the ignitrons and firing gear which they replace. It was therefore decided to mount the rectifiers in a frame to replace No. 1 ignitron frame and arrange ducting to enable them to be air-cooled by a fan and motor similar to those which formerly drew air through the water radiator. It has in fact been necessary to increase the fan speed for the new duty.

The space vacated by No. 2 ignitron frame has been utilised for a frame containing four d.c. motor contactors and other control gear referred to later.

Rheostatic brake

The use of transductors eliminates the need for a.c. load rupturing switches, and the space which these large switches previously occupied has been used for a 1000 kW rheostatic braking resistance unit of the force ventilated type. This location was the only one offering unencumbered roof space for the expulsion of resistor cooling air. Ingress for the air is provided by replacing certain windows in the corridor with louvres. Power-operated roof shutters protect the resistor from the weather when it is not in use. The location of the resistor and its cooling arrangements are less than ideal, but dictated by the exigencies of modifying an existing locomotive.

The power/brake change-over switch is located in the motor contactor frame together with certain other items previously housed with the a.c. contactors. The driver has a small power/brake change-over control switch on his desk and, after selecting ' brake ', he controls braking effort on the normal controller.

The power circuits

Fig. 4 shows the power circuits of the locomotive. As may be seen, the three-wire bridge has been retained, as this enables the existing transformer to be used unmodified, and offers some economy in rectifier fuses, compared to a double-bridge arrangement. The basic ' twice round ' tap-changing sequence is also retained.

During rheostatic braking the traction motor fields are all connected in series for excitation from the main transformer and rectifier, under transductor control.

As Fig. 4 shows, four transductors are used, each consisting of two elements. They are of the auto-self-excited type. Each element has power windings rated at 1000A (half-wave) and low current d.c. control and bias windings. The core is of uncut wound construction. The unusual proportions of the core, dictated by available

space in the reactor tank, necessitated the construction of a new coil winding machine.

The elements can each absorb the full inter-tap voltage at a line voltage of 27·5 kV. They are cooled, of course, by the main transformer oil circuit.

Control

The existing tap selector camshaft has been retained and fitted with spark tips to deal with breaking the transductor magnetising current of about 10A during downward tap changes.

To prevent almost the full voltage of a transformer half-winding being impressed across a transductor, it has been necessary to devise a mechanism to prevent 1T8 and 2T8 from closing except during the transition half way through the notching sequence.

It was originally hoped to control the transductors by switching resistances in the control and bias circuits with small contacts cam-operated by the main camshaft air engine in the intervals between main selector switch operations. However, with the existing apparatus, and without excessively prolonging the duration of notch-up, this proved impossible, and transductor control is effected by a small electrically driven camshaft with suitable interlocking to the tap selectors. This small camshaft exercises sequence control over the control and bias current by means of small switched resistance steps. These circuits are supplied from the 110 V battery.

This locomotive has had to be made so that it may be handled just like all the others of its class, i.e. with about forty notches under the driver's control. It has therefore not been possible to exploit fully the advantages of smooth control which the transductor can afford.

It is hoped soon to take the next step towards improved adhesive performance and reduction of moving parts by further modifying the equipment to eliminate the switched resistance transductor control, and fit instead magnetic pre-amplifiers. These are to be arranged as a servo-system to afford control of traction motor current at any value selected by the driver up to any speed he wishes, within the equipment capacity. Together with over-riding wheel-slip correction control this will enable the driver to make the best use of available adhesion, while maintaining the inherent stability of controlled voltage conditions for the traction motors.

Further development

The study of control problems which is involved in this development will be applicable to an equipment using silicon controlled rectifiers, as described in the opening paragraphs, as soon as these devices become economic.

Thus, as mentioned in Section I, development leads towards a locomotive with simple transformer with low-voltage tap-changing and voltage control by off-load switches and silicon controlled rectifiers, adding little to the weight and space of the main rectifiers. Control of the power circuits will again be largely by static apparatus, the whole representing, probably, something near the ultimate in low weight, tractive performance, and freedom from maintenance.

ACKNOWLEDGMENT

Acknowledgment is made to The British Transport Commission for permission to publish this article. Sections III and IV are, in all essentials, a reproduction of Papers 16 and 25 presented at the British Railways Electrification Conference held in London in October 1960. The full proceedings of the Conference, including all the papers and discussions, are obtainable (price £5) from :— Publicity Officer, British Transport Commission, 222 Marylebone Road, London, N.W.1.

The Theory and Practice of Nitriding

A. GOFFEY, M.Sc., F.I.M., Chief of Laboratories, Liverpool and Netherton Works

NITRIDING, a process introduced by A. Fry in 1920, may be defined as a method of case hardening steel by surface absorption of nitrogen. It is therefore superficially similar to case hardening by absorption of carbon but is distinct from this in procedure and is of wider application.

As with case hardening, nitriding finds its main application in connection with parts demanding extreme resistance to wear, such as shafts, cylinder liners and gudgeon pins, where the high surface compressive stress induced by nitriding also improves fatigue resistance. But many complex and intricate parts which cannot be case hardened by carburising, because of inevitable distortion, are quite amenable to nitriding. Gears are an instance when this freedom from distortion can materially reduce production costs. The increased load-carrying capacity of nitrided gears over soft gears has made possible considerable reduction in size and weight of marine gear trains (Fig. 1). Tools, particularly dies, are another instance where the high wear and abrasion resistance conferred by nitriding is invaluable, particularly in the use of dies for plastic moulding.

Nitrided surfaces retain their hardness at any temperature below the original nitriding temperature, a great advantage over carburised cases, which begin to soften at quite low temperatures.

For low production and relatively large components nitriding is a somewhat expensive process, owing to the special equipment and rather lengthy cycle time involved, but it becomes competitive with carburising when applied to high production small parts, owing to its inherent simplicity, cleanliness and invariable consistency, together with the small amount of handling required.

The process

The feasibility of nitrogen-hardening had been the subject of previous study, but it was not until Fry realised the necessity of the nitrogen being in nascent or atomic rather than molecular form that any progress was possible.

Ammonia gas when heated dissociates into its constituent elements of nitrogen and hydrogen, giving molecular nitrogen and hydrogen as the final products. At the instant of dissociation, the nitrogen is freed in the atomic state, and it is in this form and before combination with another nitrogen atom that it is sufficiently active to diffuse into the

Fig. 1—An unusual application of nitriding : a 4 ft. dia. bevel reduction gear for a ship's propeller drive

surface of steel to form metallic nitrides. Compounds of metals with single elements, such as carbon, silicon, and boron are generally hard and brittle, nitrides being no exception. However, to quote Fry, " The hardness of the nitrided layer is not to be attributed to the inherent hardness of the nitrides themselves, but rather to the influence exerted by them on the properties of the space lattice of the iron ". This can be interpreted as a distortion of the regular lattice formed by the iron atom in the crystalline structure of the steel.

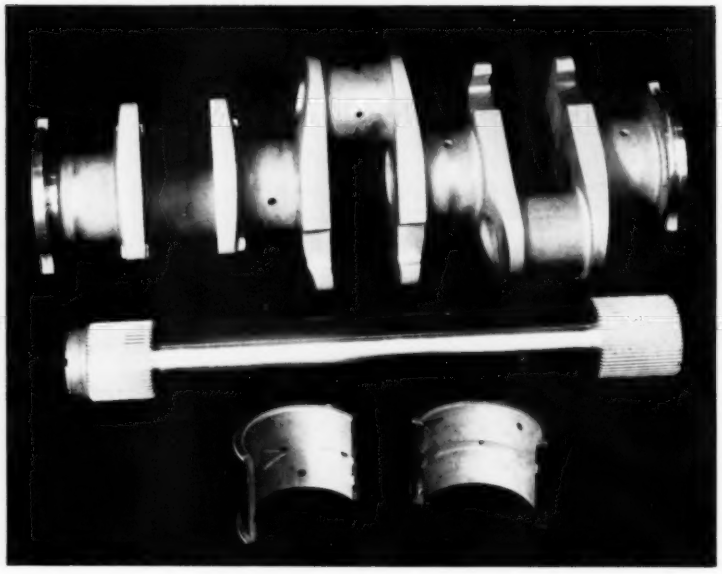


Fig. 2—Components of the Napier ' Deltic ' diesel engine after nitriding. A three-throw crankshaft, a quill shaft and a pair of big-end bearing shells

While iron and its usual alloying elements will all form nitrides, consideration of the thermo-chemistry of this formation shows that aluminium, chromium and, to a lesser degree, molybdenum are the most likely and necessary additions to promote nitriding. Fig. 3 illustrates a micro-section through a typical nitrided component, clearly showing traces of nitride (the white areas) on the surface skin and flakes of precipitated free nitrides in the general case structure.

Basically then, the process consists of the simple operation of heating components of appropriate material, suitably heat-treated beforehand, in an atmosphere of ammonia gas for a period of 10-100 hours at about 500°C. As no high temperatures or shock treatments, such as quenching, are involved and the process is carried out in a protective reducing atmosphere, parts can be treated in the finish-machined condition. No final finishing is necessary, apart from lapping or polishing.

Distortion is negligible. However, after nitriding the case is in a state of high compression, so that when any part is unsymmetrically masked for protection against nitriding, or an unwanted case is unsymmetrically removed after nitriding (e.g. on the internal periphery of a semi-circular shell), the resultant one-sided relief of this stress will cause very severe distortion. This compressive stress in the case is illustrated in Fig. 4, which shows a flat steel strip after nitriding one flat surface only, the other side having been protected by tinning. The resulting arching of the strip corresponds to a compressive skin stress of approximately 70 tons/sq. in.

Plant required for nitriding

The fundamental simplicity of the process is reflected in the plant required. This consists of a sealed container for the work, with inlet and outlet pipes for the ammonia gas, and an electric resistance furnace. Except for very small containers, it is necessary to have an internal fan to give even distribution of the gas and uniform heating.

The containers are fabricated from a heat resisting nickel-chromium-iron alloy, as are also any internal fittings such as the fan. Jigs or racks for holding the work are made of a similar material or, if in mild steel, must be protected against the action of the ammonia, heavy nickel plating or vitreous enamel being quite efficient. The ammonia pressure being very low (1 in. - 2 in. w.g.) the lid

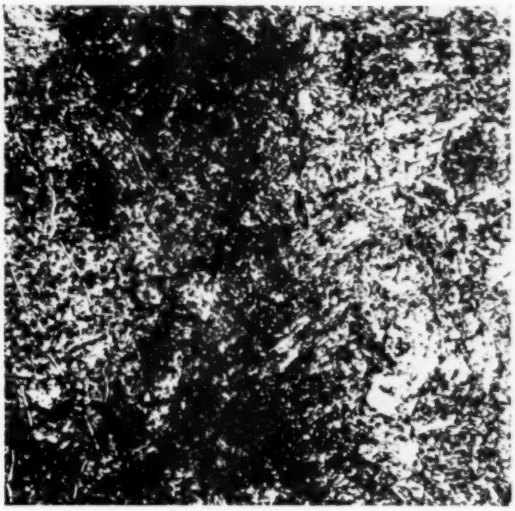


Fig. 3.—A micro-section of nitrided steel

can be sealed quite simply, usually by seating it in a trough filled with powdered chrome ore.

Close temperature control is essential. This is maintained by a recording controller pyrometer, often supplemented by additional control and safety indicator controllers. Ammonia is supplied from cylinders, the flow being controlled by pressure reducing valves and flowmeter, dissociation being monitored by an absorption pipette tapped into the outlet pipe from the containers.

The furnaces are of two general types, box (Fig. 5) or pit. It is usual to provide two or three containers per furnace to allow purging and cooling externally while one container is in the furnace under heat. In practice the work is loaded in the container which is then purged of air by ammonia, brought to the required temperature and maintained at this temperature for the prescribed time. It is then cooled to about 100/150°C with ammonia still flowing to avoid oxidation before opening. Ammonia dissociation is measured at approximately hourly intervals while the work is under heat.

Nitriding steels

Nitriding steels used in the U.K. are the original 'Nitralloy' type chromium-molybdenum-aluminium steel, En.41, and chromium-molybdenum steel En.40. En.41 produces a very hard case (950-1000 Vickers diamond hardness) for extreme wear resistance, and En.40 nitrides to approximately 750-850 V.d.h. with a tougher type of case. The case depth produced by En.41 is usually somewhat deeper than that with En.40 for a given cycle. En.19 and En.20, chromium-molybdenum steels with considerably less chromium than En.40, respond to nitriding quite well (case hardness 600/650 V.d.h.), but are not generally recommended except as an expedient. These two latter steels

Fig. 4—Strip steel nitrided on upper surface only, showing arching due to stress in the case

are not accepted nitriding steels and are not balanced in composition to ensure consistent results. The following table lists their percentage alloy compositions :—

	C	Si	Mn	Cr	Mo	V	Al	S	P
En.40	0.1/0.3	0.1/0.35	0.4/0.65	2.9/3.5	0.4/0.7	—	—	0.05 max.	0.05 max.
En.40C ..	0.3/0.5	0.1/0.35	0.4/0.3	2.5/3.5	0.7/1.2	0.1/0.3	—	0.05 max.	0.05 max.
En.41	0.25/0.45	0.1/0.45	0.65 max.	1.4/1.8	0.1/0.25	—	0.9/1.3	0.05 max.	0.05 max.
En.19	0.35/0.45	0.1/0.35	0.5/0.8	0.9/1.2	0.2/0.35	—	—	0.05 max.	0.05 max.
En.20	0.2/0.45	0.1/0.35	0.4/0.7	0.5/1.0	0.5/0.8	—	—	0.05 max.	0.05 max.

American and European steels are generally similar, although some use is made in Germany of a 2% chromium steel with or without molybdenum and vanadium. This steel will nitride to about 650 V.d.h.

There is an American steel of the En.41 type with the addition of about 3½% nickel. This nickel addition induces precipitation hardening in the core during the nitriding after suitable pre-nitriding heat treatment, which can raise the core tensile properties from 60 to 85 tons/sq. in. ultimate tensile strength and raise the core hardness from 275 to 415 Brinell. The nickel addition toughens the case with some moderate reduction in hardness. This steel has the significant advantage of possessing a core of relatively good machineability before nitriding and the automatic development of really high tensile properties in the finally nitrided condition.

The austenitic stainless heat-resisting and high-expansion steels respond, but only poorly, to nitriding. The maximum case depth obtainable in practice is 0.003 in—0.005 in and it is advisable to impose a special pre-treatment of etching and flash copper plating to remove the passive oxide surface film found on these steels. Nitriding markedly reduces the corrosion resistance of stainless steels.

In all the above steels, chromium and aluminium are the dominant nitride formers. The role of molybdenum is to promote resistance to tempering during the nitriding operation and to inhibit any tendency to the temper–brittleness sometimes induced in alloy steels by prolonged heating around 500°C ; molybdenum is also reputed to enhance toughness in the case. To avoid the development of temper-brittleness in nitriding, nitriding steels are produced from specially selected casts particularly low in content of phosphorus and even residual tin and copper. This is specially true of En.40 steels.

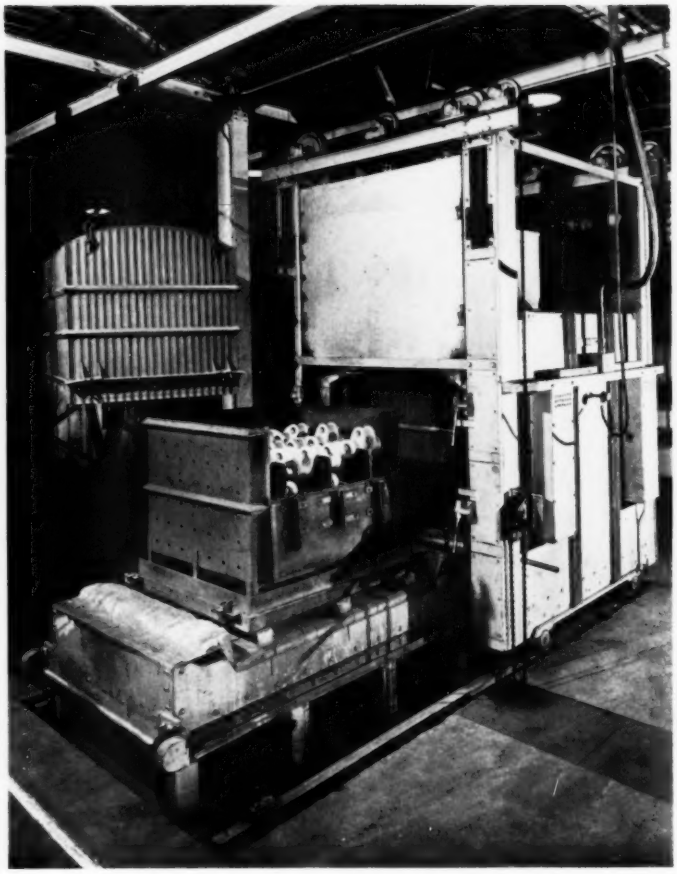


Fig. 5—A nitriding furnace of the box type, showing a batch of crankshafts withdrawn after treatment

Heat treatment

A wide range of intrinsic core mechanical properties can be obtained on these steels by hardening and tempering, subject to the limiting ruling sections specified in BS.970. En.40C is particularly interesting, being designed for a minimum tensile strength of 85 tons/sq. in. on sections up to 2½ in with useful elongation and impact values.

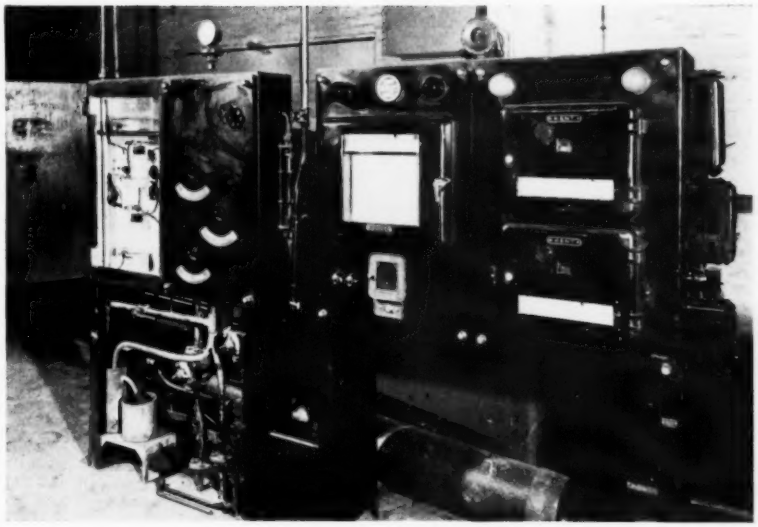


Fig. 6—This instrument panel includes the pyrometers recording and controlling the temperature of the furnace shown in Fig. 5, and the apparatus controlling the flow of ammonia gas from the pressure vessels to the container housing the workpiece under treatment

This heat treatment is necessary both to develop the desired core properties and to produce a uniformly sorbitic structure and absence of free ferrite, both of which conditions are essential for successful nitrogen hardening. The treatment must be carried out sufficiently early in machining to allow for subsequent removal of any surface decarburisation, either from forging or heat treatment, which would otherwise seriously prejudice successful nitriding. Except for simple symmetrical parts requiring a minimum of machining, it is most desirable to interpose one or more stabilising heat treatment operations between rough and finish machining, to remove any machining stresses introduced after original heat treatment which would otherwise cause distortion during nitriding.

In the U.K. nitriding is generally carried out at about 500°C, the cycle time at this temperature being 12-100 hours according to case depth required, with an ammonia dissociation 12-16%. This temperature will produce the maximum case hardness of which the material to be nitrided is capable. Slightly higher temperatures, e.g. the 525-535°C general in American practice, accelerate the process but with a reduction in case hardness. Where a lesser degree of hardness can be tolerated, a very useful cycle consists of nitriding at 535°C for five-to-eight hours and then raising the temperature to 570°C for double the time at a lower temperature with dissociation values of 20%-25% and 35%-45% respectively. This materially increases case depth and toughness with a more gradual transition from case to core. The American proprietary 'Floe-nitriding' process is very similar to this latter two-stage cycle, but uses a very high 80%-85% dissociation in the high temperature stage, which is claimed to reduce the brittle white surface layer to negligible proportions. The high dissociation stage induces diffusion rather than further nitriding.

Typical results obtained on En.40 steel are detailed below ; En.41 will produce case depths and hardness approximately 20% higher for similar cycles.

Temperature	Time	Depth	Hardness
(deg. C)	(hr)	(in)	(V.d.h.)
500	12	0.005	
	24	0.008	
	72	0.012	850/900
	96	0.015	
535+575	5+10	0.015	
	8+17	0.020	725/800

The aluminium-free En.40 type steels will generally produce higher case hardness when heat-treated to higher tensile strength ranges ; this is not so with En.41.

Selective nitriding

Selective nitriding is achieved by stopping-off the areas to be left soft by coatings of tin, copper or tin-bronze. These are generally applied by electro-plating to a thickness of 0.0003 in.-0.0005 in. Tin bronze (approximately 10% tin) has come into increasing favour of recent years. It is very effective and can safely be left on the parts after nitriding. Hot tinning by blow-pipe is quite effective as an expedient, but is messy and inconvenient. An efficient stop-off paint can be prepared by heavily loading a suitable lacquer with finely powdered tin ; this is really a variant of hot tinning, the lacquer having a fluxing action as the parts are raised to nitriding temperature. Nitriding temperatures above 500°C are apt to cause flaking-off of excess tin and some occasional soft spots on surfaces to be hardened when paint is used.

Testing

Testing for small lightly loaded parts is usually confined to hardness determination, usually Rockwell N or Vickers diamond pyramid with 2½ kg-10 kg load according to case depth, with a pilot test bar or component sectioned for metallographic determination of case depth. Aircraft and other critical parts are always accompanied by an Izod impact test piece, protected against nitriding, and heat-treated previously with the work, for detection of any temper-brittleness induced during nitriding. When the parts are too bulky or otherwise unsuitable for normal hardness testing, the Shore Scleroscope can be used with advantage.

Post-nitriding machining is mostly unnecessary owing to the negligible distortion associated with the process, but it is usual to remove the bloom or white surface layer from wearing surfaces, this being effected by honing or lapping. No machining allowance need be made for this, owing to the very slight growth (0.0003 in./0.001 in. dia.) which occurs during nitriding.

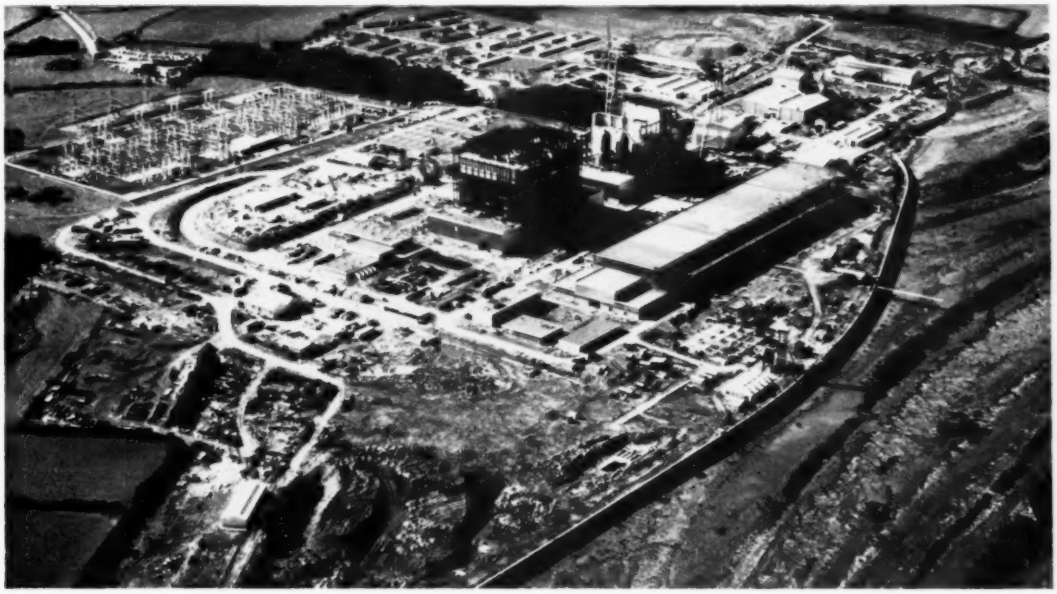
Normally, nitrided surfaces should never be ground owing to the danger of cracking, although parts nitrided by the two-stage cycle can be safely ground by techniques suitable for carburised case-hardened surfaces.

Designing for nitriding

When designing a part that is to be nitrided, symmetry of the nitrided areas should be attempted in order to avoid distortion due to the internal stresses induced in the case. A long keyway in a shaft, for example, will cause bowing of the shaft during nitriding. Sharp corners are undesirable owing to concentration of nitrides at the apex causing excessive brittleness. The use of nitrided cases should be avoided when any risk of battering impact is likely.

Recent developments

Among recent developments is the carbo-nitriding process, which combines gas carburising and nitriding, and is rapidly superseding cyanide salt bath carburising. Pressurising the ammonia container has been adopted recently in the U.S.A. in order to accelerate the normal nitriding process, and there are active developments in surface hardening titanium and its alloys by nitriding.



[photo: Central Electricity Generating Board]

Hinkley Point nuclear power station as it was last September. In the left background can be seen the switchyard

Hinkley Point After Three Years

Started towards the end of 1957, Hinkley Point nuclear power station is taking impressive shape on the coast of Somerset, a few miles from the town of Bridgwater. Most of the building and civil engineering work is done and the main effort is now increasingly towards completion of the mechanical, electrical and nuclear engineering works. Three years have gone by and in another three this giant station will be feeding its 500,000 kilowatts into the Central Electricity Generating Board's supergrid network. The half-way stage has been passed.

The English Electric, Babcock & Wilcox, Taylor Woodrow atomic power group have achieved an impressive programme of completed work. Both reactor buildings, 180 feet tall, already have their 67-foot diameter, 3-inch thick, spherical steel pressure vessels housed inside the thick concrete protective walls. These vessels—into which will go the graphite nuclear moderator and uranium fuel elements—having first been prefabricated into circular sections, were lifted into the reactor buildings by the 400-ton capacity Goliath crane and then welded together to form massive spheres weighing 1,700 tons.

The task of the Goliath crane was virtually completed with the lifting into position a few weeks ago of the last of the twelve boilers, whose sections have been brought by sea from Glasgow and welded together in the site workshops. Soon this massive crane, which has been a landmark for miles around, will be dismantled ready for moving across England to Sizewell on the Suffolk coast. There it will be used in the construction of an even larger nuclear

No. 1 reactor, with the Goliath crane in the background. All six boilers, three at each end of the reactor building, are in position. (November 1960)

[photo: Central Electricity Generating Board]

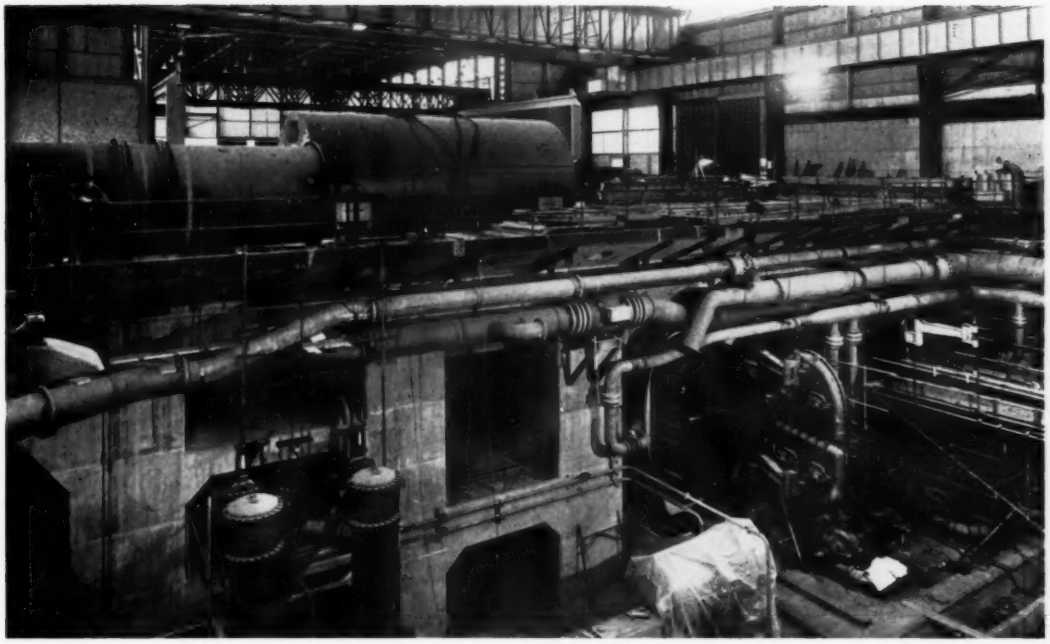
power station to be built by the Group.

Inside the reactor buildings, whose exteriors are already glazed, work goes on with the installation of a multiplicity of heavy and light equipment. One of the many unique tasks to face the site engineers was the stress-relieving of the pressure vessels.

Twelve 'English Electric' motors, each of 7,100 hp, are being installed to drive the gas blowers which serve to circulate the carbon dioxide gas carrying the heat from the reactors to the boilers. The blowers themselves, whose manufacture has been shared between 'English Electric' and Babcock & Wilcox are also being erected in the blower houses and the 6 foot diameter gas ducting between the pressure vessel, boilers and blowers is being fitted and welded together.

The work of fitting the studded tubing into the boilers under rigidly maintained conditions of cleanliness is well advanced, and the same clinical conditions will be observed when the machined

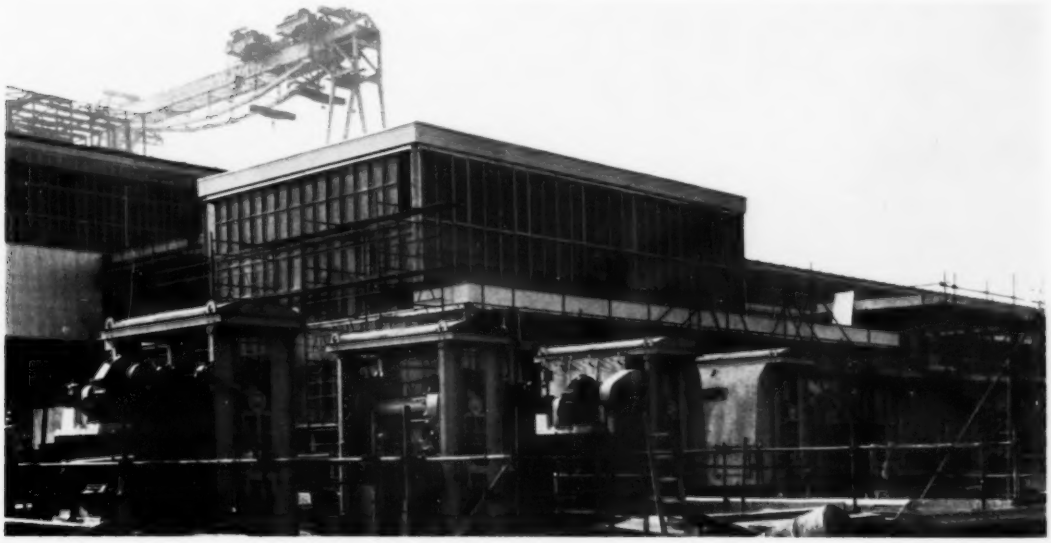
Electrical heating elements are used for stress-relieving the pressure vessel and associated parts. Elements are here being secured to the diagrid which supports the graphite pile inside the pressure vessel



[photo: Central Electricity Generating Board]

Inside the turbine hall. One of the six 93·5-MW main turbo-alternators under erection. (November 1960)

Thirty-five million gallons of water an hour are used by the steam condensing system. This view is of the pumphouse and in the foreground, the band screen filtering drives. (November 1960)



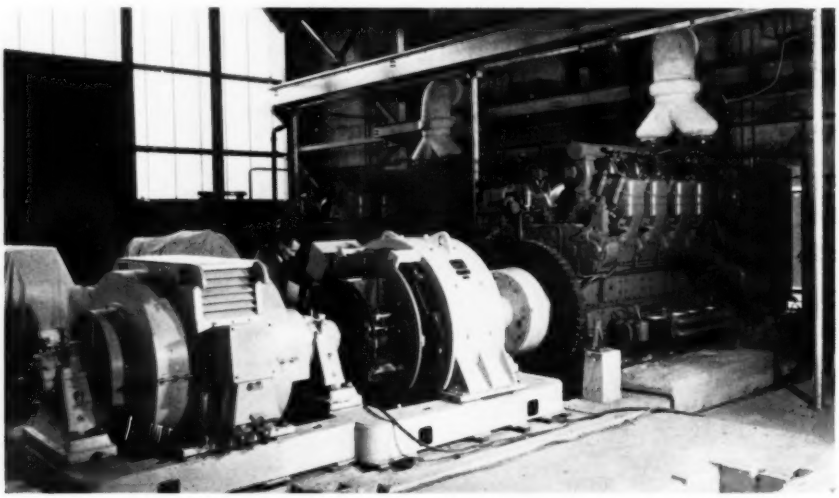
graphite blocks are stacked to make the reactor ' pile ' inside the pressure vessels.

The condensers and turbines are being installed in the completed building of the turbine hall, and delivery is being made of the main set alternators. The 11 MVA station transformers, 110 MVA generator transformers and auxiliary transformers are also being delivered. Switchgear is being installed in the electrical annexes and the control room panels fitted. The Company is also supplying the main switchgear in the distribution compound, on which work is well advanced.

Diesel engines will supply the standby power for Hinkley Point and all five 900 hp. ' English Electric ' diesel engines with their motor generator sets are installed in the diesel house. Other major plant now on site includes the water treatment and chlorination plant.

The condenser cooling water civil works and plant which represent such an important component of the station are practically completed. Band screens, main valves and pumps are being, or have been, installed.

The various miscellaneous buildings including canteen, welfare block and fuel store are rapidly being completed. The administration block is ready and is in fact now occupied by the Central Electricity Generating Board.



One of the five 900 hp. diesel/motor-generator sets now installed. These sets will be used as stand-by power for the station

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